Arnold Schwarzenegger
Governor

SACRAMENTO MUNICIPAL UTILITY PHOTOVOLTAIC (PV) PROGRAM: PERFORMANCE INDEXING SYSTEM AND PROGRAM PROCESS REVIEW

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Innovations Small Grants
- Energy Systems Integration
- Transportation

SMUD Photovoltaic (PV) Program: Performance Indexing System and Program Process Review is the final report for the SMUD Performance Indexing System and PV Program Process Review project, (Contract Number 500-00-034) conducted by Southwest Technology Development Institute. The information from this project contributes to the PIER Renewable Energy Technologies program.

For more information on the PIER Program, please visit the Energy Commission's Web site at: http://www.energy.ca.gov/pier or contact the Commission at 916-654-5164.

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Abstract

The performance index (PI) is a figure of merit for the performance of photovoltaic (PV) systems. The performance index is a ratio that compares the system actual performance to the system predicted performance. The Sacramento Municipal Utility District (SMUD) has installed a large number of PV systems in its service area. In 2003, the Southwest Technology Development Institute, a research department at New Mexico State University, developed a dedicated performance index software program for SMUD to use in monthly assessments of its several hundred PV systems. Southwest Technology Development Institute staff was also contracted to review the many processes involved in the SMUD PV program and document these processes. The performance index processing has identified numerous residential PV systems that routinely fail to produce the energy expected (based on system specifications). Southwest Technology Development Institute Engineers performed field surveys and evaluated nine of these underperforming residential PV systems in the Sacramento area.

Project team found causes of poor system performance to be shading, inverter-related problems, PV module problems, and wiring problems.

Procedures are outlined in this report that should allow SMUD to increase the safety, quality, durability, and reliability of future PV systems under SMUD ownership and of customer-owned PV systems connected to the SMUD grid.

Tree shading is a problem that can easily be solved if the homeowner cooperates. SMUD should develop a short pamphlet to explain the effects of shading to its PV customers.

Keywords: Solar, photovoltaic, PV, performance index, PI, PV module, irradiance, insolation, shading

Executive Summary

Introduction

The Sacramento Municipal Utility District (SMUD), with support from the California Energy Commission, contracted with Southwest Technology Development Institute at New Mexico State University to support its performance indexing system for monitoring the more than 900 photovoltaic (PV) systems installed in the SMUD service area. The PI system is used to compare the actual metered energy output data from these PV systems to a computer-modeled predicted output. Southwest Technology Development Institute staff also analyzed the many processes involved in the SMUD PV program, documented these processes, and recommended improvement actions.

Project Objectives

The first objective of this project was to develop and document the performance indexing software system, train SMUD staff in its use, and recommend future enhancements to the PI system. The second objective was to document and analyze the use of the performance indexing (PI) program by SMUD personnel and to review and document the many other processes that support SMUD's PV program. The following were the detailed objectives of the project:

- Develop a performance indexing (PI) software package to provide comprehensive and current information on the operating health of each grid interconnected PV system.
- Document the operation of the software system.
- Train SMUD staff on the use of the software system.
- Recommend future enhancements to the performance indexing system.
- Document and analyze the various SMUD PV program processes.
- Make recommendations for these PV program processes.
- Perform field tests on several low performance systems and document results and recommendations.

Project Outcomes

Software: Southwest Technology Development Institute completed a software package that uses monthly weather data and the characteristics of the PV systems to predict the electrical production of each system for each month. SMUD information technology staff developed a software package that accesses the actual PV output meter data (from a conventional utility watt-hour meter) for each PV system and compares the meter data to the predicted energy production. The program listed each PV system and its performance characteristics, and identified underperforming systems for SMUD maintenance staff.

PV Program Process Review: There are six processes involved in the SMUD PV program. Several departments within SMUD are responsible for these various processes. These processes are briefly described here. More details and the recommendations for improvements can be found in the body of the report.

- **Photovoltaic System Installation Process.** The Residential Audits and Inspection Services Department sells and designs PV systems under the PV Pioneer II residential program.
- **Customer Service and Service Notification.** The Customer Service Department answers PV billing questions and responds to customer repair requests.
- **Zero Meter Readings.** The Customer Service Department also submits service notifications for zero meter readings. Zero meter readings are found when the account is reviewed for the cycle. If there is a zero meter reading, a service notification is issued and submitted to the SMUD maintenance planner.
- **PV Statement Process.** The Revenue Collection Billing Department generates the "Year End Settlement" statement for all residential PV system customers. There are two meters installed at each residential home with a PV system. One meter is used for the energy in and out of the home, and the other meter measures only the PV system's energy output (and some data input).
- **PV Maintenance Process.** The PV Maintenance Department operates and maintains SMUD PV systems. Most SMUD systems have been residential, but SMUD has implemented other systems used by churches, businesses, etc. Under this process, only PV Pioneer II systems were evaluated.
- **Performance Indexing.** The Renewable Generation Assets Department reviews the PV system performance. To date the performance indexing system has been used to detect underperforming systems.

Site Inspections: During the week of December 5, 2005, engineers from Southwest Technology Development Institute inspected nine residential PV systems in the Sacramento area that showed low performance indexing numbers, indicating poor performance. They were assisted by SMUD PV service technicians. Engineers performed different levels of tests on different systems and identified several underperforming systems as a result of obvious shading. Below are the results of a few system tests that illustrate recurring problems.

Electrical measurements and physical inspections were used to identify the reasons for poor performance at each of the nine systems tested. The project team observed some trends based on these results. In decreasing order of importance, the project found causes of poor system performance to be: shading (by trees and permanent structures); inverter-related problems (units operating out of specification or intermittently, either due to inverter problems, or to low performance PV modules); PV module problems (broken and/or degraded); and wiring problems (particularly, failed wire nuts and fuses). These are discussed briefly below and in detail in the body of the report.

Shading: Tree shading is the most common reason for poor performance found among the systems tested. The reduced output is a function of how the array is wired and which modules and module strings are shaded at a given time.

Inverter-related Problems: The inverters in question were all Xantrex SunTie STXR2500. Several units were measured at direct current operating voltages below specifications. This may represent an inverter power point tracking problem or can be the result of a severely degraded PV array output.

PV Module Problems: The project team observed many problems with one PV module type: Dunasolar EPV-40. Engineers found delamination in modules from several arrays, and the area opposite the module wiring block was particularly susceptible. Performance of all Dunasolar arrays was markedly less than the nameplate.

Wiring Problems: In several systems, numerous wire nuts had failed within rooftop string combiner boxes. This finding was unexpected and disturbing to the project team. Potential reasons for failures may include an improper temperature rating, improper installation procedure and manufacturing defects.

Recommendations

Recommendations are made regarding the residential installation process, the customer service and service notification process, the zero meter readings process, the PV statement process, the PV maintenance process, and performance indexing.

Tree shading is a problem that can easily be solved with the homeowner cooperation. If tree shading is explained to the customer, some will choose to trim trees where possible. Others will not, or cannot where trees are in neighboring yards. Solar access rights may be an issue in these cases. SMUD should develop a short pamphlet to explain the effects of shading to its PV customers. Many homeowners with shaded PV arrays told the project team they knew their systems were producing less than in the past, but did not recognize this obvious cause.

The degrading performance of the Dunasolar EPV-40 modules will likely become worse and more prevalent with time. As these modules decline, performance indexing values will continue to drop and recurring alerts from permanently low performance indexing values will be common. The nameplate ratings for these failing systems can be manually adjusted downward to eliminate recurring low performance indexing alerts. The warranty terms for these modules are critically important. SMUD should produce a procedure to upgrade these systems, replace the modules, or remove the systems when no longer a benefit, or are possibly a liability, to the utility.

SMUD should create a program to identify and review the performance indexing data from all Xantrex STXR2500. Where possible, field follow-up should be conducted to locate other systems in need of service.

The last recommendation addresses the wire nuts. The wire nut manufacturer has discontinued these items, and the manufacturer gave no reason for discontinuing this series. SMUD should try to identify if similar failures of these products have been observed elsewhere, or, at a minimum, to obtain recommendations for replacement of these products.

Benefits to California

The software package developed for SMUD use should be, with modifications, suitable for use by any California utility to monitor the performance of PV systems in its service area. The following results and benefits, while specific to Sacramento service area, are likely to represent the population of PV systems installed throughout California. These benefits include:

- Analysis of the operating characteristics of a fleet of operating PV systems to determine actual electrical production.

- Identification of underperforming systems and dispatching of repair technicians to troubleshoot and correct any problems.
- Identification of failure-prone aspects of installed systems and performing feedback to system manufacturers, designers, and installers.

The review of the process SMUD uses and the resulting recommendations will benefit California by allowing more customers to take advantage of the program and improvements in the operation of the installed PV systems, with a resulting increase in energy output.

This project helps in quantifying PV performance issues, both past and future, which supports potential performance-based incentives in California.

1.0 Introduction

The Sacramento Municipal Utility District (SMUD) has installed more than 900 photovoltaic (PV) systems in its service area. Each PV system has a separate utility Watt-hour meter to measure output (and some data input) that is read every month. The Southwest Technology Development Institute (SWTDI) developed a software system to identify underperforming PV systems. SMUD contracted with SWTDI, a research department at New Mexico State University, to develop and document the performance indexing (PI) software system, train SMUD staff in its use, and make recommendations for future enhancements to the performance indexing system. SWTDI staff also reviewed and provided recommendations on the various processes that are involved in the SMUD PV program. This report has three parts: (1) a description of the PI program and its use; (2) a description of the processes utilized in the SMUD PV program and recommendations for improvements; and (3) documentation of PV system field tests conducted by SWTDI and SMUD staff on underperforming PV systems that were identified by the performance indexing (PI) program.

1.1. Project Objectives

The following were the project objectives:

- Develop a PI software package to provide comprehensive and current information on the operating health of each grid-interconnected PV system.
- Document the operation of the software system.
- Train SMUD staff on the use of the software system.
- Form a reliable basis for calculating total hourly PV generation and make recommendations for future enhancements to the PI system.
- Review and provide recommendations on the processes utilized in the implementation of the SMUD PV program.
- Perform field tests of selected low-performance customer-sited PV systems in the SMUD program.

1.2. The SMUD Performance Index (PI) Program

The performance indexing (PI) is a figure of merit used with PV systems. It is the ratio that compares the energy produced by the PV system to the energy expected. In 2003, SWTDI developed a dedicated PI program for SMUD to use in a monthly assessment of SMUD's several hundred PV systems. In 2004–2005, SWTDI upgraded the software, documented its design and operation, and submitted these results to SMUD. This portion of the report documents the major activities and results of this effort.

1.2.1. SMUD PI: Program Description and Overview

The SMUD performance indexing (PI) program was developed to automate the process of performance index determination for all PV systems in SMUD's service territory. It integrates solar position algorithms, PV performance characteristics, meter and billing data (received from the SMUD Information Technology (IT) department), and weather data collected from a local weather station. Each month, SMUD PI calculates an expected energy output for every system in SMUD's service territory. SMUD PI requires three sets of data:

1. PV system description (including size and orientation).
2. Energy produced.
3. Solar radiation received by the array.

The 2003 version of the SMUD performance indexing (PI) program used a very simple correction for array temperature and provided no support for one-axis tracking. In 2004, both of these features were upgraded.

The result of SMUD PI processing each month includes statistics related to the 900-plus individual PV systems, overall fleet-wide performance, and the scheduling of service notifications for systems whose underperformance the software has recognized.

1.2.2. Documentation of Data Flow and Processing with Recommendations

The objective of this task was to document and analyze the use of the performance indexing (PI) program by SMUD personnel and other processes that support its PV program. This task focused on SMUD's processes that are used for its PV Pioneer II program from system installation to system maintenance.

The deliverable for this task supplied specific recommendations to improve or streamline the processing of data and the scheduling of service notifications when needed.

1.2.3. Assessment of SMUD Staff Safety and Reliability Practices

The objective of this task was to document the safety practices of SMUD technical staff, review the procurement process for SMUD-owned systems, and make recommendations.

The deliverable for this work supplied a review of SMUD's technical staff and their practices, and provided suggestions for changes to the procurement documents for SMUD-owned PV systems that would increase system reliability and safety.

1.2.4. Limitations of the Process and Potential Improvements

The major limitations to the accurate determination of performance indices in the SMUD PV fleet are:

- The use of one central weather station for irradiance.
- The reliance on modeled array temperature rather than measurements.
- The lack of site specific information about shading (when present).

Ideally, the performance index for each array is based on the irradiance and array temperatures measured at the site of the array. Because this is not practical for the large number of PV systems in the fleet, calculation of performance indices for all systems is based on a single weather station and modeled array temperature. Similarly, PI values for a given array will be in error when there is shading due to local obstructions. Lack of site-specific shading conditions for the PV arrays makes this an unavoidable source of error.

Improvements to the program may be possible to increase the overall accuracy of system modeling in some areas. These areas include:

- Derating expected system performance for reduced inverter efficiency at low power levels.

- Developing a shading profile for each system that accounts for shading from known trees or structures throughout the day and the year.

2.0 SMUD Performance Indexing (PI) Program

2.1. Project History and Timeline

The SMUD performance indexing (PI) project has had two distinct phases. The phases are discontinuous in time and were funded by different sources.

Phase I began in 2002 with funding from the U.S. Department of Energy (DOE). In January 2002, SWTDI staff and Sandia National Laboratories (SNL) met with the California Energy Commission and SMUD to offer technical support for PV deployment and use in California. At this time, SWTDI agreed to develop the SMUD PI program, one of the original projects in Energy Commission-funded SMUD Renewable Generation Research (ReGen) program.

Phase I continued until 2003, during which time the SMUD performance indexing (PI) program was developed, installed, tested, and revised several times.

Phase II began in 2004 with SMUD issuing an award to SWTDI for additional support for the SMUD PI process program. The Phase II tasks and deliverables included modifications and improvements to the SMUD original PI program and the development of complete documentation of all aspects of its use by SMUD personnel.

Phase II began in fall 2004 and concludes with this report.

2.2. SMUD PI Program Overview

The SMUD PI program calculates energy expected from each PV system in the SMUD fleet and compares it with the generated energy recorded for the system by an on-site meter over the approximately one-month period between meter reads. A comprehensive description of the process, algorithms, and data requirements is presented in this section of the report.

2.3. SMUD PI Program Data Requirements

The calculation of PV system energy production requires the following parameters: PV system description including specification of major components and array orientation (tilt and azimuth), measurement of the effective solar radiation in the plane of the array, and measurement of the average array temperature. Once calculated, the simulated energy can be compared to the actual energy produced by each PV system as recorded by the monthly reading of its dedicated meter.

SMUD PI program relies on data from two sources. The SMUD IT department provides a monthly report with all system description parameters and the monthly energy (meter) readings. A local weather station provides the necessary solar radiation and ambient temperature data. These two sources of data are described below.

2.3.1. Energy Produced

SMUD has installed a dedicated production utility Watt-hour meter on each PV system in its territory. The PV meter is read monthly. The IT department runs a monthly report that documents all PV system data from the previous month. The energy parameters from this report that the SMUD PI program needs are: meter read-from date, meter read-to date, and kilowatt-hour (kWh) produced.

2.3.2. Solar Radiation Received by the Array

The hundreds of PV arrays in the SMUD database have different orientations in azimuth and slope. To determine the PI value for an array, SMUD performance indexing (PI) program must first calculate the effective radiation received by each array (also known as the plane of array irradiance). On an hour by hour basis, plane of array irradiance is determined using two measured solar radiation parameters and the solar position (calculated). The two solar parameters needed for this calculation are direct normal irradiance and diffuse irradiance. Solar position is derived based on date, time of day, the site latitude and longitude, and the set of equations that model the motion of the sun. A separate program, named SMUDAzEl (SMUD Azimuth and Elevation), was written to perform this function. For each PV system, SMUD PI program calls SMUDAzEl during its normal execution.

2.4. SMUD PI: Use of the Program

The product of the SMUD PI program is a monthly PI value for each PV system in SMUD territory. These PI values can be used to determine which systems are functioning properly and which are underperforming and need servicing.

PI values derived in this way are not perfect. One source limiting its accuracy is the use of a central weather station to estimate radiation on roofs that may be 20 or 25 miles away. An additional (and common) source of error is shading of otherwise properly functioning arrays. Other sources of inaccuracy can be misreported system parameters such as array orientation or slope, improperly calibrated radiometers, or an inaccurate real-time clock setting in the weather station data logger.

Even with its limitations, SMUD PI results can be used to unambiguously identify most underperforming PV systems. By internally coupling this with repair scheduling, SMUD provides a valuable service to its customers before most discover that they need it, and after repair or replacement, additional valuable renewable energy is obtained. In addition, the accumulation of PI values over years will enable SMUD engineers to identify performance trends and estimate system lifetimes for the many PV technologies in use.

2.5. SMUD PI—Data Requirements

SMUD PI requires data from two sources. The SMUD IT department provides a monthly report with all billing and system description parameters, and a local weather station provides the necessary solar radiation data. These two data sources are described below.

2.5.1. SMUD IT Monthly Meter Report

The SMUD IT department keeps all records in a large SAP database, and runs a query to extract the necessary data for all PV systems on a monthly basis. This report is run 10 days after the start of each month by an employee in the SMUD Business Technology Projects Department.

The monthly report is produced in text format. It is named with a common convention, starting with the two letters "PV," and includes the month, day, and year when it was generated. For example, PV20030910.txt is the report run on September 10, 2003. Each report has several hundred records, one for each PV system.

Records have 39 fields. Not all fields contain data for every record. Most records contain some blank fields. Fields are delimited using the tilde character (hex character 0x7E). Using the UNIX convention, each record is terminated with a single line feed character (hex character 0x0A). Table 1 shows the 39 fields presently included for each PV system record in the monthly SAP report.

As described later in this document, SMUD PI converts the original text report from its native UNIX format to a Windows-compatible format in which fields are terminated using the convention of two characters, carriage return, and line feed (hex characters 0x0D 0x0A). This file is renamed with a *.fix* extension.

Table 1. Field Assignments for SMUD SAP PV Monthly Report.

Field Number	Description	Example
1	DEV LOC	1001346
2	DG#	1104
3	OWNR	SMUD
4	METER	613109
5	FROM	2/11/2002
6	TO	3/12/2002
7	KWH	286
8	LOCATION ADDRESS	6802
9		ELM STREET
10		
11		
12	METER SET	3/31/1994
13	SYSTEM RATING	3.6
14	MODULE TYPE	SIEMENS M55
15	# OF MOD	84
16	INVERTER TYPE	OMNION 2500
17	# OF INVERTERS	1
18	ROOF LAYERS	DOUBLE
19	ROOF SUBSTRATE	1/2" PLYWOOD
20	SLOPE	45
21	ROOF STRUCTURE	RAFTER
22	EST ENERGY	100
23	COST P/WATT	$3.50
24	CONTRACT DATE	8/26/2001
25	E	10
26	SE	5
27	S	2
28	SW	15
29	W	20
30	BUSINESS PARTNER	RICHARD E. WEBER
31	PHONE #1	
32	PHONE # 2	
33	MAILING ADDRESS	6802
34		ELM STREET
35		
36		
37		SACRAMENTO
38		CA
39		95826

Source: SMUD

2.5.2. *Weather Data*

Solar radiation has several components and is measured with a variety of instruments. The SMUD performance indexing (PI) program requires two solar components to calculate the plane of array irradiance on each PV array. These components are direct normal irradiance and diffuse irradiance.

A weather station containing a rotating shadow band radiometer, capable of supplying the necessary solar data, is located at Bergquam Energy in Sacramento. This weather station belongs to James Bergquam, a mechanical engineering professor at California State University, Sacramento. Professor Bergquam allowed SWTDI to reprogram the radiometer to add hourly data to its normal collection and allowed SMUD engineers to collect the data nightly via modem.

The radiometer is based on a CR10x data logger from Campbell Scientific, Inc. Windows software for enabling the collection from the radiometer was installed on a SMUD computer equipped with a telephone modem. This software is named PC208W ver. 3.2. The PC208W software contains a setup entry for each data logger the user has. This entry for the radiometer data logger contains the telephone number and the designated time to call automatically each night. Manual collection on-demand is also available at any time. The user invokes PC208W, selects Connect from the main menu, and presses the Connect button. New weather data are automatically collected and appended to the existing weather data file. The data logger can store three weeks of data before the oldest records are overwritten, and the data is normally downloaded on a weekly basis.

Table 2 shows a single hourly record from the weather station. In addition to recording radiometer-based readings, the weather station data logger is used to monitor performance of a solar thermal system and takes dozens of readings of flow, temperature, etc., that are not used by SMUD PI. The description of these fields changes and is of no consequence to SMUD PI. SMUD PI uses six fields in the weather data files. The specific field assignments needed are called out in the configuration file, explained in a later section. At present, these are:

- Year—field 2 (value 2002 in the example Table 2).
- Julian Date—field 3 (value 249 in Table 2).
- Time—field 4 (value 1200 in Table 2).
- Direct Normal Irradiance—field 11 (value 686.15 in Table 2).
- Diffuse Irradiance—field 12 (value 52.218 in Table 2).
- Ambient Temperature—field 8 (value 22.636 in Table 2).

Note that the “time” field is always kept set to Pacific Standard Time. Neither the data logger nor any subsequent process uses daylight savings time.

Table 2. Hourly Record from Rotating Shadow Band Radiometer Weather Station.


```
41,2002,249,1200,13.28,20.346,20.636,22.635,36.536,467.21,686.15,52.218,694
.84,24.468,-12.869,-0.00604,-0.01653,0.00146,-0.27256,0,-
59.654,239.84,3.4951,17.606,-2.8981,1.0353,-
0.00176,0,1.2574,0,0,0,0,0,5.7409,-3.0194,0.8922,2.2375,-0.13757,-0.05174,-
10.58,-13.996,56.272,0.66349,3.3423,-
0.55008,5.5416,6.1567,6.0738,69.4,17.175,14.973,15.831,13.724,23.432,30.613,
75.206,13.054,68.959,30.487,15.628,67.747,69.334,69.391,13.861,75.141,18.06
8,13.983,15.521,16.814,13.289,14.829,12.522,15.535,17.082,15.474,21.565,16.7
33,16.802,16.913,16.805,16.58,1.2811,0.02744,-2.1553,-
0.10977,617.15,13.82,0.99992,0.00903,0,0,0
```


Source: SMUD

2.6. SMUD PI—The Integrated Process

SMUD PI was designed to run in a fixed hierarchy of directories. The root directory can be of any name. Four files must be found in this directory as well as two subdirectories with the following description:

- **SMUD_PI1.exe**—This is the executable program that oversees all PI processing and produces the output files.
- **Config.dat**—This is an ASCII text file that contains the configuration data needed to run SMUD_PI1. It can be edited from within SMUD_PI1, as desired.
- **SmudAzEl.exe**—This is an executable file called automatically (in the background) by SMUD_PI1 for each PV system in the database. It produces the irradiance files that are stored in the Setup subdirectory (see below).
- **SAP meter file**—This file (SAPData91004.TXT, in Figure 3) is produced monthly by the SMUD IT department. It contains the database of PV systems, their descriptions, and the latest meter readings for each.
- **CSI subdirectory**—This subdirectory contains the weather data files.
- **Setup subdirectory**—This is a working directory for the temporary storage of intermediate files output from SmudAzEl.exe and used by SMUD_PI1 in its PI calculations. The files in this directory are overwritten for each system as it is processed.

Figure 1 illustrates the contents of the SMUD_PI directory.

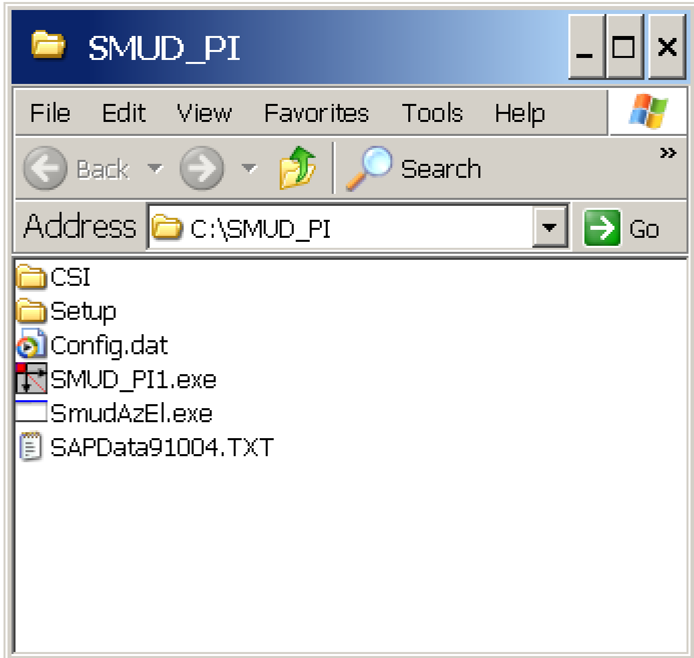

Figure 1. File and subdirectory structure to run SMUD PI

Photo Credit: SMUD and SWTDI

2.7. Running SMUD PI

Running SMUD PI is done by double clicking the SMUD_PI1 icon SMUD_PI1.exe When SMUD PI is launched, a basic home screen is presented with four main buttons and a Quit button, shown in Figure 2.

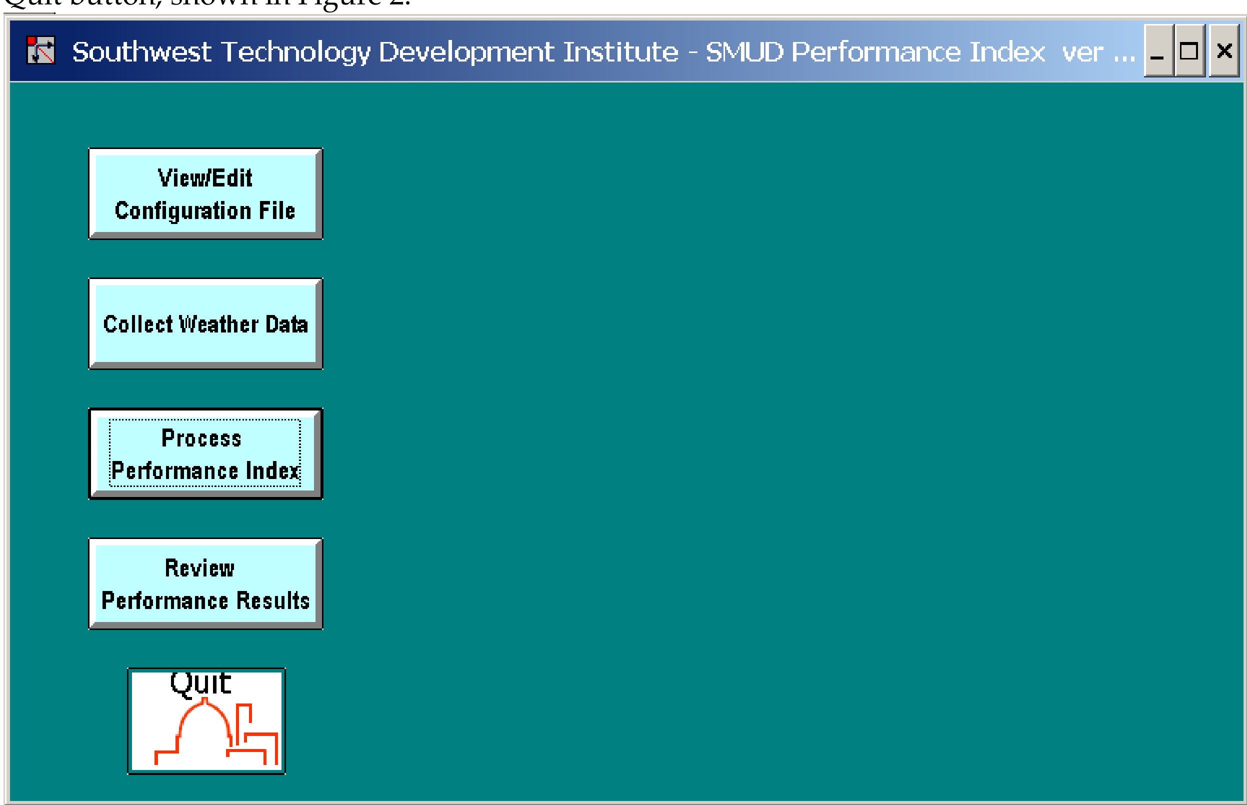

Figure 2. SMUD PI home screen

Photo Credit: SMUD and SWTDI

The first button the user should press is the View/Edit Configuration File button. This brings up a page of configuration parameters as shown in Figure 3. SMUD PI is configurable so that it can run in different ways, using different input data files, without having to be recompiled each time. The text file, Config.dat, is provided for this purpose.

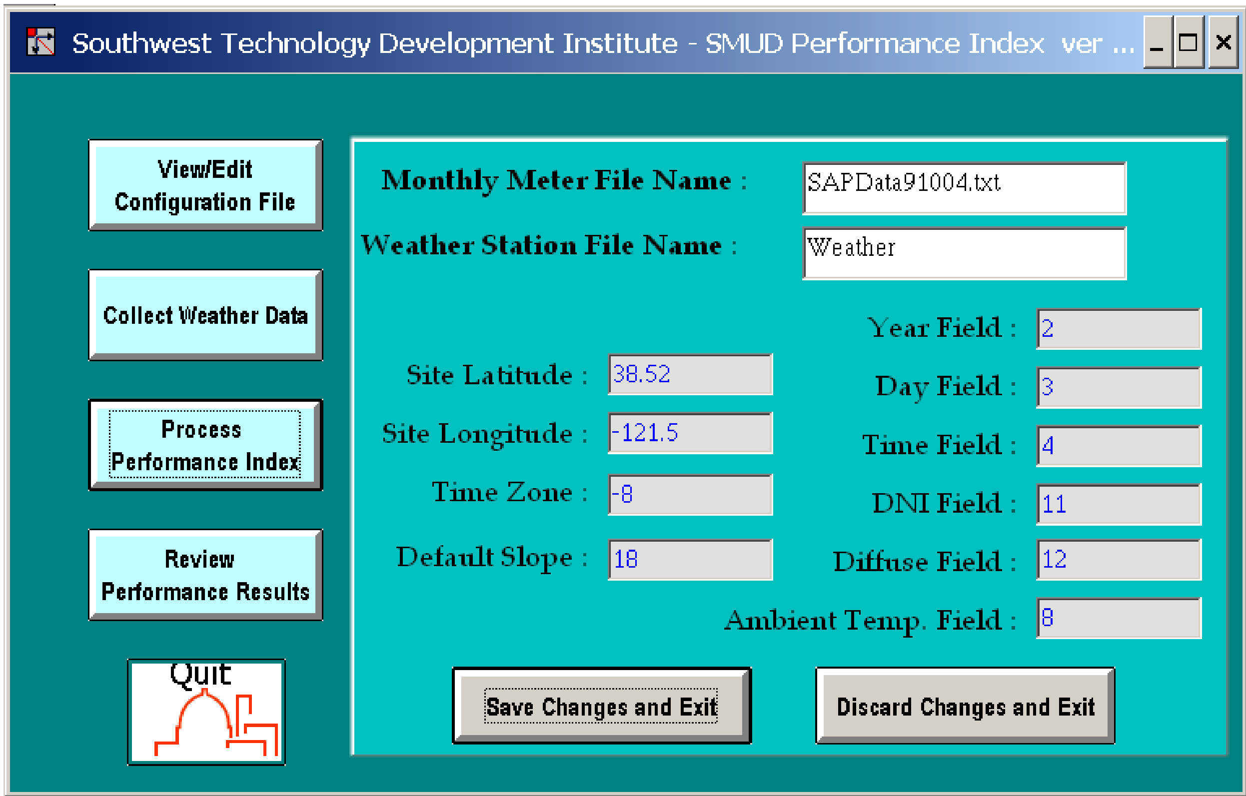

Figure 3. View/Edit Configuration page

Photo Credit: SMUD and SWTDI

The field assignments are straightforward. The name of the current PV SAP Meter file must be provided. The name of the weather data file is next. Note that this file must be located in the CSI subdirectory and have the .dat extension. The Site Latitude and Site Longitude shown in Figure 6 are those for Sacramento. The Time Zone field is –8, representing eight time zones west of the Prime Meridian. The next six numeric entries identify the fields needed in each record of the weather data file. Finally, a default slope value is provided for use when that field is empty in the PV system database. The user can review the parameters and press the Discard Changes and Exit button if they are correct. Or he may update any field(s) and press Save Changes and Exit to record them.

Once the contents of the Configuration File are updated or verified, the user will typically press the Collect Weather Data button. This brings up the Weather data page shown in Figure 4.

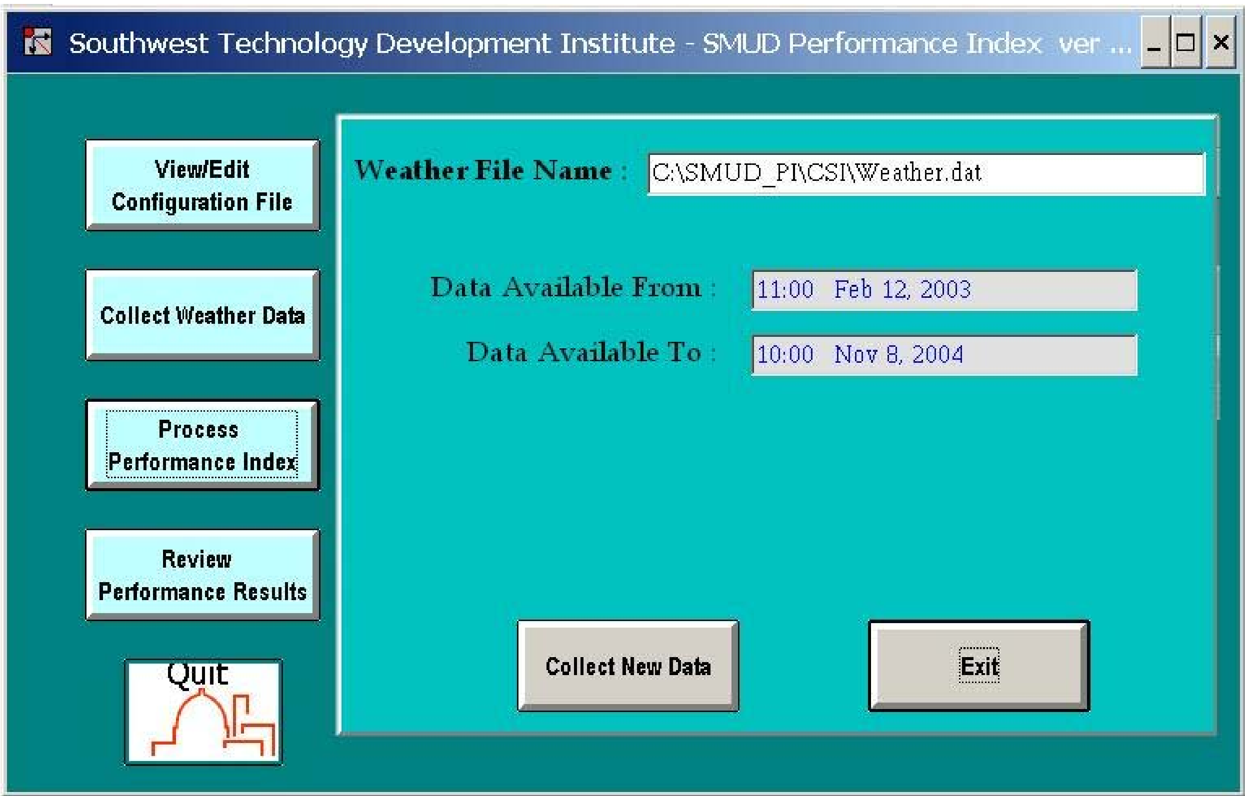

Figure 4. Collect weather data page.

Photo Credit: SMUD and SWTDI

The principle value of reviewing this page is to verify that the weather data file contains data for the month being processed. With each day's collection, the new weather data are appended to the weather data file in chronological order. The page shows the range of dates and times for which there are weather data in the data file. The user can press Exit to close the page after reviewing these parameters.

At this point, the user can press the Process Performance Index button. This brings up the page shown in Figure 5. The user has the option to process the PV systems one by one by pressing the Step button. Normal operation, however, is to press the Process All button. This causes SMUD PI to calculate and record PI for every PV system in the Meter File.

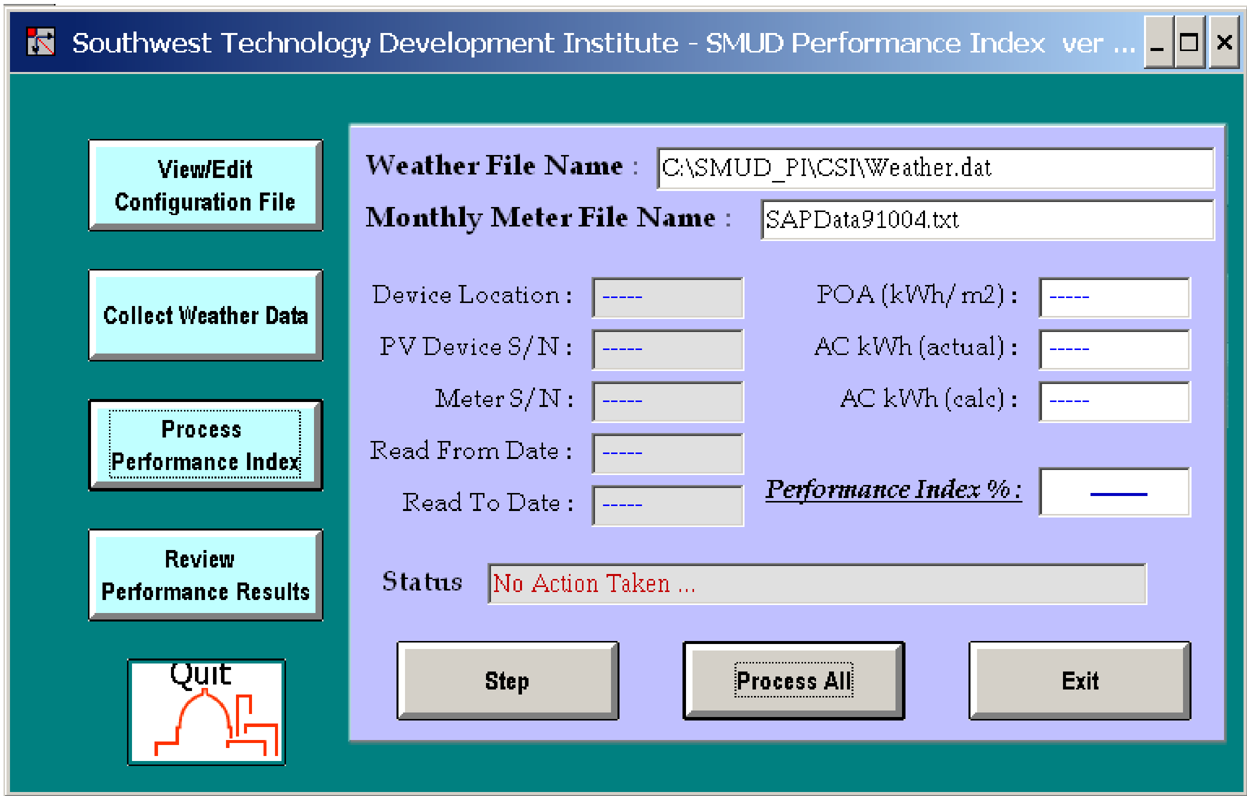

Figure 5. Process performance index page

Photo Credit: SMUD and SWTDI

Once all of the systems are processed, the user can launch Excel to review the results or quit the program. After quitting, the directory will be seen to have files shown in Figure 6.

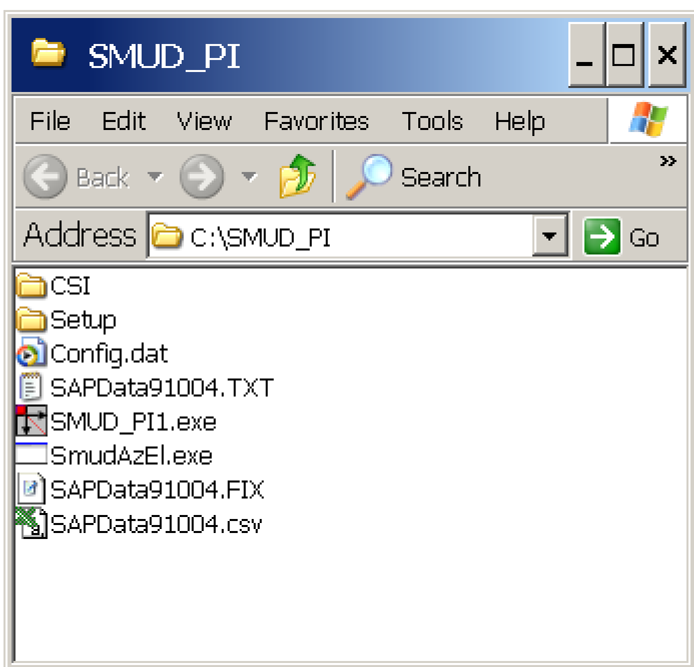

Figure 6. SMUD PI Directory after processing

Photo Credit: SMUD and SWTDI

The two new files both have the same name as the SAP meter file, but with new extensions:

- ***.fix**—This file is the Windows-compatible version of the original SAP produced meter file.
- ***.csv**—This is the output file. This file is in ASCII text form but with comma separated values compatible with and automatically importable into Excel.

2.8. SMUD PI Output File

As mentioned, the output of SMUD PI is a file with the same name as the SAP meter file but with the extension .csv. This file duplicates the meter file but adds the PI output data, as seen in Table 3.

Table 3. SMUD PI output .csv data file

DevLoc	DG Num	Meter S/N	Read From	Read To	kWh act	kWh calc	PI (%)	
1001346	1104	613109	7/11/2003	8/8/2003	381	634.44	60.05	Error Codes: 8;
1001485	2031	870296	7/11/2003	8/8/2003	635	696.34	91.19	Error Codes: 0
1004807	1926	767645	7/22/2003	8/20/2003	343	359.66	95.37	Error Codes: 0
1005346	1924	870219	7/22/2003	8/20/2003	345	383.6	89.94	Error Codes: 0
1005735	1477	615988	7/22/2003	8/20/2003	363	632.36	57.4	Error Codes: 8; 9;
1005749	1173	613295	7/22/2003	8/20/2003	0	673.52	0	Error Codes: 4 ;
1005782	1490	721794	7/22/2003	8/20/2003	363	748.36	48.51	Error Codes: 8; 9;
1005794	1001	610866	7/22/2003	8/20/2003	358	449.01	79.73	Error Codes: 8; 9;
1006239	1511	316873	7/3/2003	8/4/2003	438	982.07	44.6	Error Codes: 8 ;

Source: Data provided by SMUD PI

Four fields are of interest: kWh actual, kWh calculated, PI (%), and the Error Codes. The kWh actual is the energy recorded by the PV system output kWh meter. The kWh calculated is the calculated energy expected based on the system description and solar data. The PI (%) is the ratio of these two values. The Error Codes are necessary because not every entry in the PV system database is complete. When all required fields (13 total) are present, complete processing, called Level 1 processing, is performed and Error Level equals zero. When that is not possible, incomplete entries may still be processed using default values, if the minimum six fields are present. Table 4 shows the error codes, and fields necessary for Level 1 and Level 2 processing. Defaults are used for the following fields during Level 2 processing, when needed:

- Number of inverters—1.
- Roof slope—38.5° (latitude of Sacramento).
- All modules are South-facing.

When insufficient data are present for Level 2 processing, a PI value of zero is entered. Note that a PI value of zero can also be a legitimate result of Level 1 or Level 2 processing when the PV system has been offline for the entire month and the kWh actual entry is zero.

Note that in Table 4, the system rating field (row M) in the SMUD database is an AC rating that is either the Energy Commission rating for this system or an equivalent calculated (for some systems) by SMUD engineers.

Table 4. SMUD PI Level 1, Level 2 processing and error code assignments

			Level 1	Level 2
A	DEV LOC	1001346	X	X
B	DG#	1104		
C	OWNR	SMUD		
D	METER	613109	X	X
E	FROM	2/11/2002	X	X
F	TO	3/12/2002	X	X
G	KWH	286	X	X
H		9232		
I		HENLEY WAY		
J				
K	LOCATION ADDRESS			
L	METER SET	3/31/1994		
M	SYSTEM RATING	3.6	X	X
N	MODULE TYPE	SIEMENS M55		
O	# OF MOD	84	X	
P	INVERTER TYPE	OMNION 2500		
Q	# OF INVERTERS	1		
R	ROOF LAYERS	DOUBLE		
S	ROOF SUBSTRATE	1/2" PLYWOOD		
T	SLOPE	45	X	
U	ROOF STRUCTURE	RAFTER		
V	EST ENERGY	100		
W	COST P/WATT	$100.00		
X	CONTRACT DATE	8/26/2001		
Y	E	10	X	
Z	SE	5	X	
AA	S	2	X	
AB	SW	15	X	
AC	W	20	X	
AD	BUSINESS PARTNER	JACK H BARNES		
AE	PHONE #1	916-366-9633		
AF	PHONE # 2			
AG		9232		
AH		HENLEY WAY		
AI				
AJ		[redacted]		
AK		SACRAMENTO		
AL		CA		
AM	MAILING ADDRESS	95826		

Level 1 PI: all required fields are present
Level 2 PI: some fields absent, PI uses default parameters

Error Codes

0	All fields present
1	Read From Date missing
2	Read To Date Missing
3	Read To < Read From
4	kWh missing
5	System Rating Missing
6	Number of Modules Missing
7	Number of Inverters Missing
8	Roof Slope Missing
9	Sum of Orient values less than Number of Modules
10	Read From or Read To outside avail weather data range

Example:
Error Codes: 1;2;6;8

Source: Data provided by SMUD PI

2.9. SMUD IT–PV System Description Data

The SMUD SAP database also contains descriptions of all PV systems in its territory. Most system entries have been reviewed and are complete. The monthly report reproduces these parameters for use during PI processing. The system parameters SMUD PI needs are:

- System rating—the AC system rating derived by the Energy Commission rating procedure.
- Module type—manufacturer and model.
- Number of modules—total number of modules in the array.
- Inverter type—manufacturer and model.
- Inverter quantity—number of inverters.
- Roof slope—in degrees.
- Number of modules in each of five azimuth orientations—E, SE, S, SW, and W.

Some of the arrays in the SMUD PV fleet have been installed with different segments mounted on roof surfaces that face in many directions. The energy production of these systems is calculated as the numeric sum of the contribution from each planar array segment.

2.10. SMUD PI Program Algorithms

SMUD PI uses the following algorithms to determine monthly system values:

- Plane-of-array irradiance algorithms.
- Average module temperature algorithm.
- PV system energy estimation algorithms.

2.10.1. Plane-of-Array Irradiance Algorithms

Solar radiation is defined as having a direct component (radiation that comes from directly from the solid angle subtended by the solar disc) and a diffuse component (coming from all directions as a result of clouds and scattering by atmospheric aerosols). Knowing these components, time of day, and the position of the sun, the effective plane-of-array irradiance can be calculated. The weather data files contain hourly average values for direct and diffuse irradiance in the Sacramento area.

SMUD PI must calculate the plane of array irradiance on each PV array using equations of the motion of the sun. The equations of solar geometry are well-defined. Figure 7 shows a plot for Sacramento indicating solar position in azimuth and elevation by hour for each day of the year.

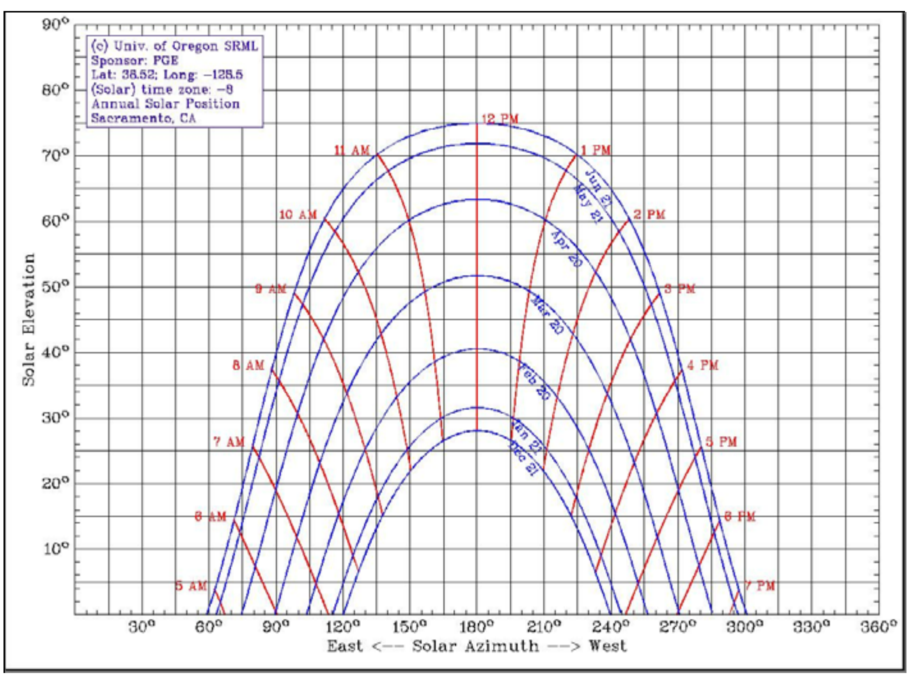

Figure 7. Sacramento solar position graph

Source: SWTDI / Info from NREL & SMUD

Public domain algorithms and source code to determine solar position and the solar incidence angle on a planar surface were obtained from the National Renewable Energy Laboratory

(NREL). The SOLPOS 2.0 program is written in the C programming language and is capable of calculating solar position accurately to 0.01°.

A C-language source file, AzElCalc1.c, was created and compiled with modified versions of the original SOLPOS 2.0 source files to create a custom executable program called SMUDAzEl.exe. SMUDAzEl.exe is designed to integrate seamlessly with SMUD PI. The output of SMUDAzEl is a file for each plane of the array containing the solar azimuth angle, solar elevation angle, and the cosine of the solar incidence angle on the plane for every hour of the billing period. These angles are later used in conjunction with the weather data to calculate effective POA on each PV array plane for every hour of the billing period.

In 2004, SMUD added support for one-axis tracked arrays to the PI program. This is implemented in the SMUDAzEl.exe program. For every hour of the month, the position of each array tracking-row is determined and the solar incidence angle to this row is then calculated. In practical terms, the geometric algorithms are identical to those used in determining solar incidence angles to a fixed array, but the array orientation (slope and orientation) is itself changing hourly.

Figure 8 shows the three source files that are compiled to create SMUDAzEl.exe. The compiler used for this process is the Dev-C++ 4.0 compiler, in the public domain. Appendix A contains the documentation for the NREL SOLPOS algorithm. This includes additional references on solar geometry.

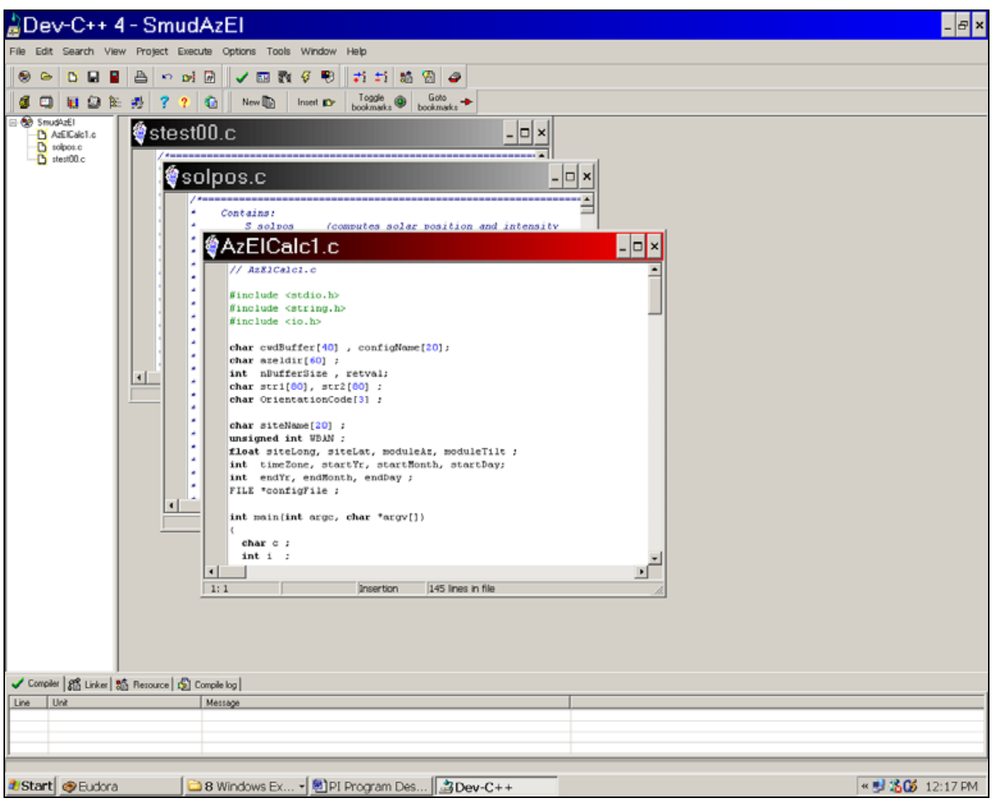

Figure 8. Source files comprising SMUDAzEl in the Dev-C++ Program

Photo Credit: SWTDI

2.10.2. Average Module Temperature Algorithm

Output of any PV array is a function of temperature with most producing less voltage and power as temperature rises. The original development of SMUD PI used a common temperature correction coefficient for all PV arrays in the SMUD PV fleet. This was updated in Phase II to use a dedicated pair of coefficients for each array type to determine a more accurate hourly average module temperature. These coefficients are supplied by the SMUD engineers and are maintained in the configuration file, Config.dat. The two coefficients are a module temperature coefficient of power (in %/°C) and a module delta temperature (in °C). The temperature coefficient is a function of the PV module type (e.g., crystalline silicon, polycrystalline silicon, amorphous silicon, CdTe, etc.). The delta temperature value is the temperature rise above ambient that the modules experience under 1-sun (1000 W/m^2), calm wind conditions. This is a function of the array mounting (e.g., rack mount, integrated roof, etc.). Typical values for a rack mount, poly-crystalline array are -0.5%/°C and 20 to 30°C. The hourly array DC energy is corrected by the following equations:

- tempcomp = 1 + ((tamb-25) + (DeltaT* 1000/POA)) * TempCoeff

  where:
  tempcomp = temperature compensation factor (dimensionless)
  DeltaT = user supplied Delta temperature parameter (°C)
  tamb = ambient temperature (°C)
  POA = plane of array irradiance = (DNI * CosInc) + Diff
  TempCoeff = user supplied array temperature coefficient (in %/°C)

2.10.3. PV System Energy Estimation Algorithms

With the appropriate weather data and SAP data, SMUD PI calculates the expected energy for each PV system in the SMUD PV fleet. The first step in the calculation of a PI value for any system is the execution of the program SMUDAzEl. This program generates and stores data files with the calculated solar azimuth and elevation for every hour in the month. It also calculates and stores the cosine of the incidence angle between the sun's position (hourly) and the plane or planes of the PV array being processed (recall, some arrays are in segments that have different orientations).

Data in the weather file are recorded hourly so array energy is calculated on an hourly basis and then summed over the monthly period. The array dc output is calculated based on solar radiation and a fixed array temperature of 25°C (77°F). This will later be temperature corrected for actual operating temperature conditions. The weather data file has hourly average values for direct normal irradiance and diffuse irradiance. SMUD PI uses these values plus the SMUDAzEl data files to implement the following equation for every hour of the month:

- P = (PV * DNI * CosInc) + (PV * Diff)

  where:
  P = hourly average Array output power (W)
  PV = Array rating in W_{dc} STC multiplied by the inverter efficiency
  DNI = hourly average direct normal irradiance (W/m^2)
  CosInc = cosine of the incidence angle between the sun at mid-hour and

array plane (dimensionless)
Diff = diffuse irradiance (W/m^2)

The output of this equation is hourly average *power*. Numerically, however, the hourly average power equals the hourly *energy* for that hour (because the period is exactly one hour).

The hourly energy is then corrected for operation at actual temperature in the same manner as the Average Module Temperature Algorithm. Using the "P" and "tempcomp" equations above, the corrected energy can be determined:

- E = P* tempcomp

  where:
  E = Array temperature corrected energy (kWh)
  P = Array uncorrected energy from above.

The hourly values for energy are summed over the month to give the predicted kWh. Because the inverter efficiencies have been factored into the system size, there is no inverter correction factor necessary.

Once estimated monthly energy for a system is known, the PI is simply the ratio of actual energy divided by estimated energy. Values over 85% indicate systems working properly. Values less than 50% indicate systems in need of attention. Those systems with values between these levels, may be partially shaded, may have minor operational problems (such as a blown fuse in a single string), or may be reading low because of some inaccuracy in the database (e.g., the array orientation is not correctly given, etc.)

In addition to fixed arrays, SMUD PI has the ability to model the output and PI for arrays utilizing one-axis tracking. The process is identical to the one described above except that SMUDAzEl is used to calculate the incidence angle on the array each hour as it moves through its tracking process. The energy expected from the array is then calculated based on this position and summed over the monthly period.

2.11. SMUD PV Program Processes

2.11.1. Objective

The objective of this section is to document and analyze the use of the PI program by SMUD personnel and other processes that support the SMUD PV program. This report documents SMUD's processes that are used for its PVII program, from system installation to the maintenance of installed systems.

Each process is a sequence of steps in which different departments contribute to making SMUD's PV Program a success. SWTDI visited with SMUD personnel in November 2004 to discuss and gather information about their PV program and the processes that are used to support this program. The following is the list of staff that SWTDI visited with:

- J. Green, Information Technology
- M. Zannakis and H. Ortiz, Residential Audits & Inspection Services – Residential Services

- O. Bartholomy, Renewable Generation Assets
- S. Brown, Revenue Collection Billing

2.11.2. Photovoltaic System Installation Process

Department: Residential Audits & Inspection Services—Residential Services

The Residential Audits and Inspection Services Department is responsible for selling and designing PV systems under the PVII Residential Program. This department also certifies the systems installations conducted by outside contractors. This process is diagramed in Appendix B1.

Process

The PV system installation process begins with a SMUD customer inquiring about a PV system installation for his/her home. The process is designed to end with a successful system installation. Not all inquiries result in system installations. Before a home is considered for a SMUD PV system, it must meet specific requirements developed by SMUD. One major requirement is that the roof must be less than five years old and have single layer composition asphalt, no redwood rafters. Other requirements include having enough roof space for installation on east, south, or west sides, and shading of less than 10% annually.

If all the necessary requirements established by SMUD are met, the customer is provided with a cost estimate of the potential PV system. At this time, customers must decide whether this is an option they would like to pursue. Typically, the customer must finance a portion of the system cost. PV systems are high in capital cost, but many customers view this investment as a method of reducing their monthly utility bills and possibly generating excess electricity to sell back to the utility.

Once the customer approves the quote and signs the contract, SMUD finalizes the design and procures the equipment that will be used for system installation. At this time, the customer must obtain the financing for the project. If financing is not obtained, the customer does not qualify for a SMUD PV system.

When financing is obtained, SMUD proceeds with verifying the site and contracting a system installer. Under the SMUD PV program, only approved PV installers are authorized to install SMUD PV systems. Within this program, the installer guarantees his workmanship only. SMUD provides all equipment necessary for the installation.

After the system is installed, a SMUD PV specialist certifies the system for workmanship and tests the system for performance.

Recommendations—Residential Installation Process

The following recommendations are made with respect to the residential installation process:

- Provide the customer with a **rough cost estimate** at the time the inquiry is made. This will eliminate the time spent designing the system and providing the final cost estimate when real interest may not be forthcoming.
- Review and approve the PV system design before the contractor installs the system.

- Consider requiring the system installer to provide the equipment for the system, which in turn would require the installer to furnish material warranties as well. The liability of ensuring long-term operation of the system would then move to the system installer.
- Formalize technical acceptance testing of the system as part of the certification process. An example inspection and certification checklist can be found in Appendix B7 and B8. Part 1 (B7) is a checklist and Part 2 (B8) is a narrative of the inspection.
- Increase the involvement of the PV maintenance department in the design, installation, and certification for all PV systems.
- Make the database of PV systems accessible to all department personnel involved in SMUD's PV program. The database should include site information, costs, operation, maintenance, etc.

2.11.3. Customer Service and Service Notification

Department: Customer Service

The Customer Service Department is responsible for answering PV billing questions and responding to customer repair requests. This process is diagramed in Appendix B2.

Process

This process begins with the customer contacting the customer service department. The customer service representative gathers the necessary information from the customer on their system. Next, the customer service representative determines whether the customer's system is under warranty (systems under the PVII program have a warranty period of five years). If the system is under warranty, the customer service representative issues a service notification in SAP and submits it to the maintenance planner. However, if the system is no longer under warranty, the customer service representative provides the customer with a list of qualified contractors to assist them with their repair.

Recommendations—Customer Service and Service Notification

The following recommendation is made with respect to the customer service and service notification process:

- A letter should be sent to customers notifying them when the expiration date of their system warranty is approaching.

2.11.4. Zero Meter Readings

Department: Customer Service

The Customer Service Department is responsible for submitting service notifications when zero meter readings are observed. This process is diagramed in Appendix B3.

Process

There are instances when the customer is unaware that his PV system has been underperforming. It is not uncommon to have months when there are zero meter readings from the customer's PV system. Zero meter readings are identified when the customer service representative reviews the accounts for the cycle. When there is a zero meter reading, a service notification is issued and submitted to the maintenance planner.

Recommendations—Zero Meter Readings

The following recommendation is made with respect to the zero meter readings process:

- Develop a function within SAP that generates a separate monthly report of zero meter readings. This report will facilitate the service notification process by the customer service representative or the Renewable Generation Assets Department.

2.11.5. PV Statement Process

Department: Customer Service

The Revenue Collection Billing Department is also responsible for generating the "Year End Settlement" statement for all residential PV system customers. There are two meters installed at each residential home that has a PV system installation. This report is useful since it provides the PV customer with a complete record of PV system generation for the given year. The report is also submitted to SMUD management for their review and further analysis of SMUD PV systems. This process is diagramed in Appendix B4.

Process

The data gathered from the PV meter is used to develop the annual report for the net PV generation. This information is retrieved from the customer bill and manually entered into a spreadsheet (Settlement Statement). This information must be verified for accurateness, and then a copy is sent to the customer.

Recommendations—PV Statement Process

The following recommendation is made with respect to the PV statement process:

- Consider generating the annual report, presently developed by the Customer Service Department for customers at year end, as an automated function within the PV maintenance tool.

2.11.6. PV Maintenance Process

Department: PV Maintenance Department

The PV Maintenance Department is responsible for proper operation and maintenance of SMUD PV systems. Most systems implemented by SMUD have been residential systems, but SMUD has implemented other systems used by churches, businesses, etc. For this report, only maintenance of PV Pioneer II systems is documented. This process is diagramed in Appendix B5.

Process

To commence this process, the PV maintenance department must receive a service notification generated from the Customer Service or Engineering Support Group. The service notification is issued through the SAP system and received by the maintenance planner, who then must prioritize all service notifications and provide work orders to PV maintenance personnel. Since the PV maintenance personnel are not involved in the design or implementation of the PV system, they must gather what information and supporting documentation they can about the system before performing the system evaluation. The PV maintenance personnel must notify the system owner of the evaluation visit before the system evaluation is conducted. A thorough evaluation is done to investigate the reported problem. The PV maintenance personnel must also determine the level of maintenance required to assess whether they can perform the repair or if a contractor must do it.

Whether SMUD's PV maintenance department or a SMUD contractor performs the maintenance, the end result is a repaired system. The responsible party who conducted the repair prepares documentation and it is submitted to the maintenance planner. The maintenance planner enters the information into SAP system.

Recommendations—PV Maintenance Process

The following recommendations are made with respect to the PV maintenance process:

- Implement a customer survey that provides feedback to gauge customer satisfaction.
- Provide the customer a written repair record for their records, if not implemented already.
- Document recurring problems with specific installation techniques or system equipment problem. This information can be useful to the Residential Services Department and contractors.

2.11.7. Performance Indexing

Department: Renewable Generation Assets

The Renewable Generation Assets Department is responsible for reviewing the system performance of all SMUD PV systems. System performance is evaluated using the PI software, which provides a tool to compare actual system output (kWh) recorded by meter readings against an expected output (kWh) based on the weather data and the system specifications. To date, the PI system has been an effective tool used to detect underperforming systems. This process is diagramed in Appendix B6.

Process

The performance indexing process uses the meter readings from SAP (received by the 10th of each month) which are captured by the PI program. The PI program compares actual output with the calculated output based on the weather data and system specifications. If the system is underperforming and remains under warranty, a service notification is issued to the maintenance planner.

Recommendations—Performance Indexing

The following recommendations are made with respect to performance indexing:

- Add customer revenue meter data to the already-prepared SAP meter file produced monthly.
- Generate the year-end settlement report for customers automatically.
- Generate the zero meter reading summary report automatically.

2.12. SMUD PI Program—Capabilities, Limitations, Possible Improvements

The SMUD PI program meets an important need at SMUD for monitoring and documenting the status of its large and dispersed PV fleet. It provides a measure of system quality assurance that was not possible prior to its development. But, its capabilities have technical limits and these are important to note.

2.12.1. Capabilities of the PI Program at SMUD

SMUD developed two separate tools for pre- and post-processing support: the Access-based PVDB2 and the PV Maintenance Tool.

The Access-based PVDB2 is a database which uses a series of macros to update the latest performance results from SAP and the PI program. These results include any changes in static data fields relating to system characteristics, or the addition of new systems, as well as the addition of monthly results for kWh produced, expected kWh, and resulting performance index for each system.

The PV Maintenance Tool allows users to access the performance histories of individual systems. Because most of the end users are more comfortable with using Excel than Access, the tool was developed to maximize ease of use of the data. This adds a few extra steps for the updating process going from the PVDB2 to the PV Maintenance Tool; however, the total monthly SMUD effort for the update process takes approximately a half hour or less thanks to the development of macros that automate the process.

Within the PV Maintenance Tool, individual customer records can be pulled up to provide all of the static data, a link to the field survey or system certification sheet, and the performance and kWh production history for the past 14 months. A screenshot of this report is shown in Figure 9.

In addition to individual customer reports, the PV Maintenance Tool allows fleet summary reports to be generated based on a number of factors including system type, orientation, performance, etc. An example of the fleet summary report generation page is shown in Figure 10.

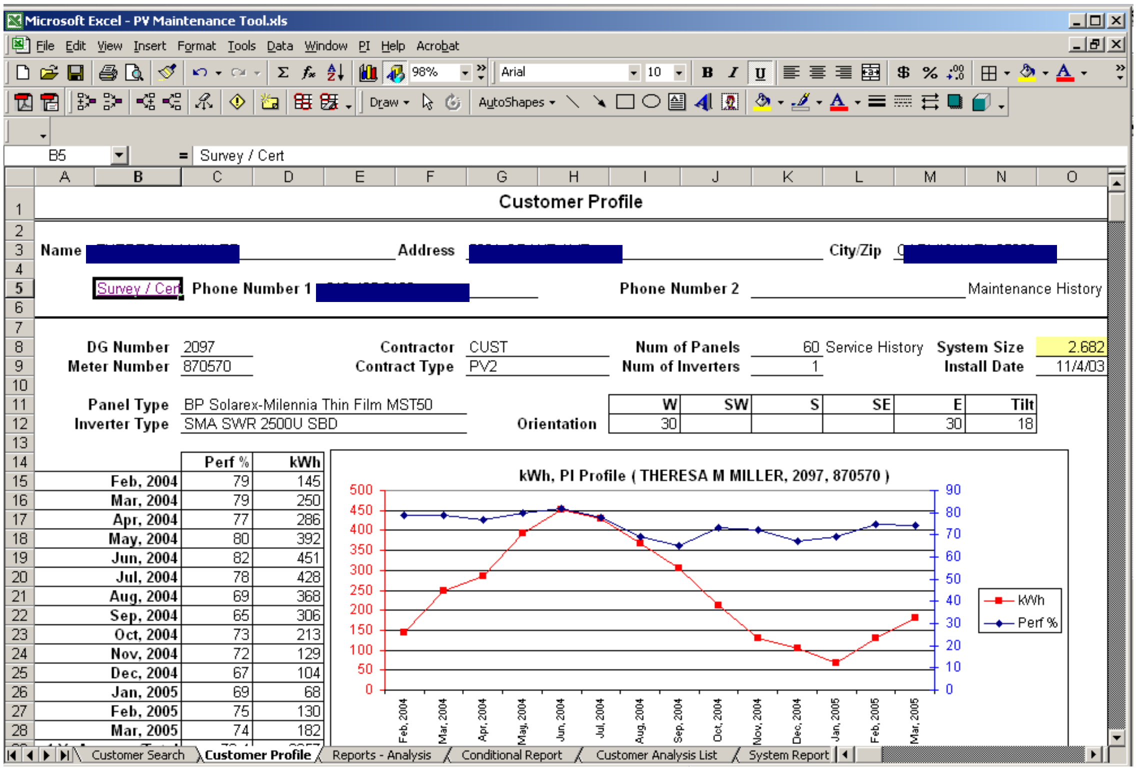

Figure 9. Customer performance profile generated in the PV Maintenance Tool

Photo Credit: SMUD and SWTDI

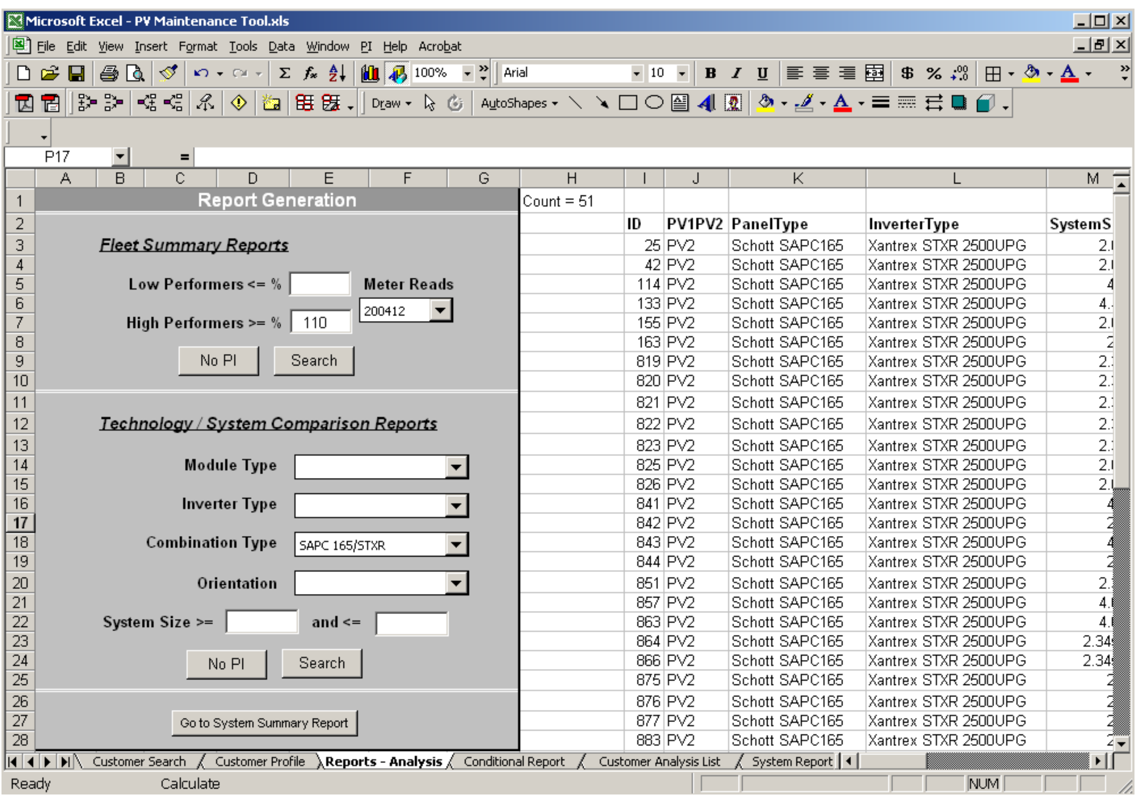

Figure 10. Report generation page for creating fleet summaries based on system characteristics

Photo Credit: SMUD and SWTDI

The results from the report generation are provided both in tabular form in the Customer Analysis list, as well as in a summary format on the Conditional Report page. These reports allow easy identification of underperforming systems, as well as comparisons from one underperforming system to several systems that are of the same type to see if the problem is system-specific or if it is a common problem to system of that configuration. The Conditional Report page is shown below in Figure 11.

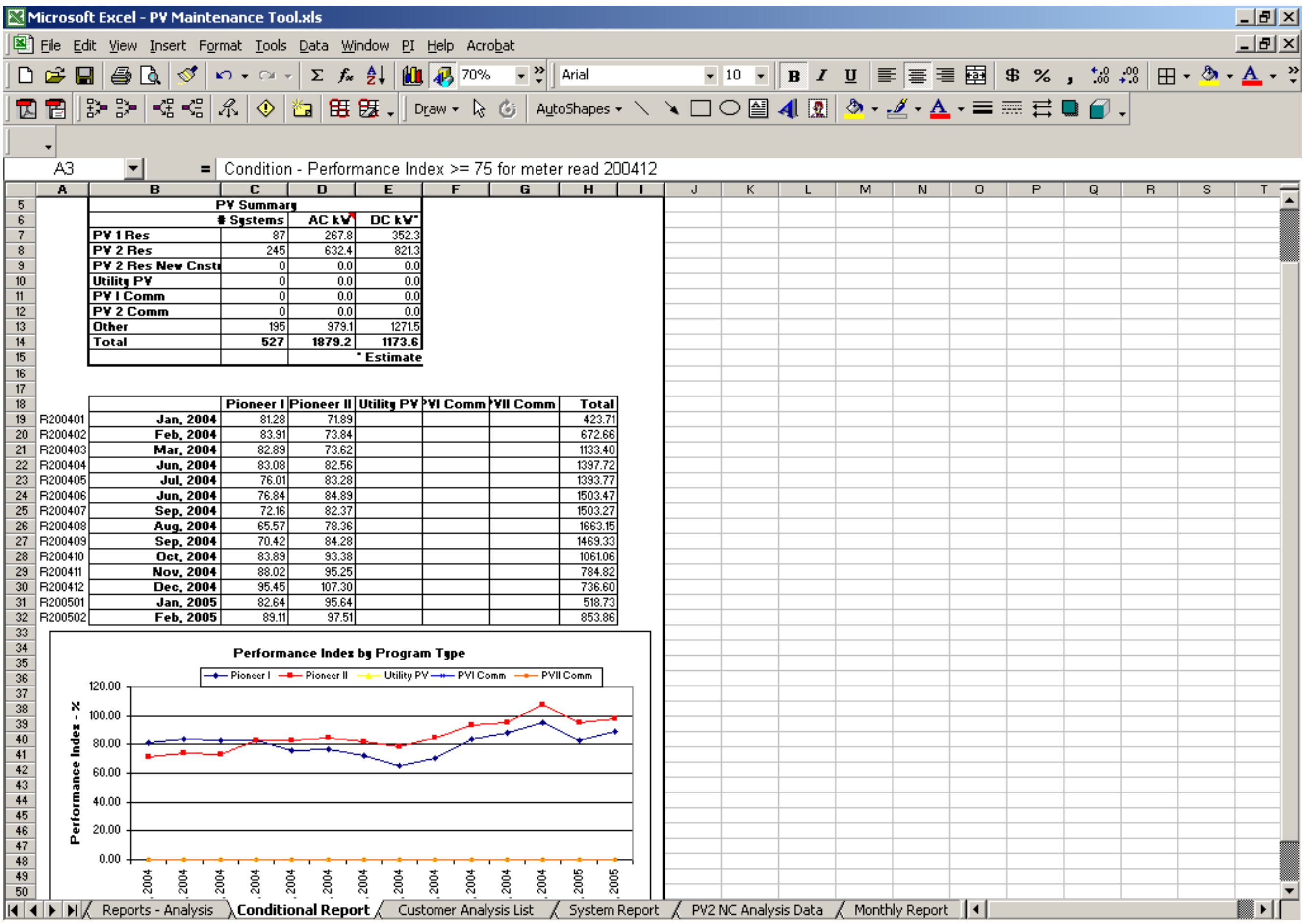

Figure 11. Condition report page of the SMUD PV Maintenance Tool.

Photo Credit: SMUD and SWTDI

The PV Maintenance Tool is also used for the creation of monthly PV reports that summarize the production and performance of the entire PV fleet each month. These reports section the systems based on the program that they were installed under, e.g. PV Pioneer 1 Residential, PV Self Install, etc. This allows program managers to track the progress of their fleets individually. The totals are summarized for the year to date and the current month, and are compared to last year's production as well as the expected production out of the fleet for the current month.

2.12.2. Limitations of the PI Program at SMUD

The SMUD PI program is limited in its accuracy by the type and accuracy of the data it uses for input and by the approximations implemented in its many algorithms.

The major limitations to accurate determination of performance index in the SMUD PV fleet are:

- The use of one central weather station for irradiance.
- The reliance on modeled array temperature rather than measurements.
- The lack of site specific information about shading (when present).
- Misreported system ratings.
- The approximations used in PV system performance algorithms.

Ideally, the performance index for any PV system is based on the irradiance and array temperatures measured at the site of the system. Because this is not practical for the large number of PV systems in the SMUD fleet, calculation of the performance index for all systems, territory-wide, is based on irradiance readings taken at a single weather station. And, territory-wide, system array temperatures are modeled based on the weather station's ambient temperature reading and user-supplied module temperature coefficients. At present, no study has been done to determine the magnitude of errors introduced by variations between the conditions at the weather station and the many dispersed systems.

A major source of error in PI value determination is localized shading. Experience with the SMUD PI program has shown that performance index values are frequently anomalously low where a given roof is shaded for all or part of the day. Shading is more common in the older neighborhoods than those more recently constructed.

A more subtle source of error in the PI values comes from misreported system ratings. The PI program estimates system production based on the system size (kW_{ac}) reported in the PV system database. In the many years of the SMUD PV program, these system sizes have been determined in different ways and by different people. If, for example, a family of PV systems has been denoted by a system size of 2 kW_{ac} where 1.8 kW would have been more accurate, the PI values for each system of this type would be artificially low each month.

Lastly, the PI algorithms themselves are only approximations for the production of typical PV systems under general conditions. In particular, no correction is attempted to the system efficiency during operation at times of low irradiance or high solar incidence angles. Low irradiance conditions result in low DC input power to the inverter and the efficiency of all inverters falls off (low) under these conditions. Similarly, PV module output is not linear with solar incidence angle and falls off (also low) at the higher angles. These shortcomings are mitigated somewhat by the fact that energy production during these conditions is a fraction of what it is during midday operation and, thus, a fraction of total energy.

2.12.3. Areas of Possible Improvement for the SMUD PI Program

There are two major areas of possible improvement in the SMUD PI implementation. The first is adding an inverter efficiency correction based on percentage of inverter rating (a complex model, but one that has been started at SNL. Second is a topic discussed recently at SMUD and with Commission staff to implement a horizon shading correction process. This complicated process would add scanned horizon profiles to the data for each PV system and correct the modeled system production accordingly.

3.0 Achieving Safe, Reliable, and Cost Effective PV Systems at SMUD

3.1. Introduction

State-of-the-art utility-interactive PV power systems have the potential to deliver highly reliable, renewable energy for many years in a safe, durable manner with little or no maintenance. However, some of the PV systems installed in the SMUD jurisdiction and elsewhere throughout California and the country are not meeting this potential for many reasons. This report outlines a procedure that should allow SMUD to increase the safety, quality, durability, and reliability of future PV systems under SMUD ownership and of customer-owned PV systems connected to the SMUD grid.

3.2. Background

The PV module has matured to the extent that most of the crystalline silicon modules installed today will produce energy for 30 years or more. The knowledge base exists in terms of experience, equipment, instructions, and codes to design and install PV systems that make maximum use of the current equipment to provide many years of excellent service. Although inverters, charge controllers, and batteries have not yet achieved the degree of reliability and longevity of PV modules, their full capabilities are often not used in many installations due to poor system design and installation techniques. Some of the problems with the deficient systems and what can be done to improve the safety, durability, and quality of new systems are addressed below. These problem areas have been observed in systems ranging from 1 kW to 750 kW. Many of the PV systems under the control of SMUD, even the newest and most recently installed systems, have these deficiencies. They have been identified from reviewing design information and wiring diagrams, inspections (evaluations for code compliance), testing (performance tests for array output and inverter performance), and analyses of data collected for long-term performance assessments (Wiles et al. 2002).

3.3. Refining the Art of PV

PV systems have the potential for long, reliable, and durable performance. PV modules are available with warranties of 25 years; these and other similar modules can be expected to deliver energy for 30 years or more. Based on the performance and degradation of crystalline silicon PV modules that have been in use for 30 years, life expectancy for these types of modules can be extrapolated to 50 years. PV-unique balance-of-systems (BOS) equipment has varying warranties (inverters up to five years, and for grid-independent systems, charge controllers up to five years, and batteries up to seven years). The electronic equipment is, for the most part, designed and constructed using solid-state components. Assuming proper installation and use, and ignoring cases of infant mortality, direct lightning strikes and other unusual surges, this equipment can have longevity measured in decades. Some of the well-designed and installed PV BOS equipment has already demonstrated 12 to 15 years of continuous operation. Other non-PV BOS equipment such as wire conductors, overcurrent devices, and switchgear are very mature (more than 100 years of development) and might be expected to outlast the PV modules in a properly designed and installed system.

To some extent, the longevity of the PV module as a power generator is unique among electrical power generators. Most typical electrical power generators (with the possible exception of hydro-electric plants) are not expected to have a maintenance-free operating life of 30 to 50 years. When these relatively high-maintenance power generators are serviced or upgraded, the connected BOS equipment is usually inspected and repaired, updated, or replaced as necessary. PV modules producing energy for 30 to 50 years pose unique requirements on associated equipment and the installation of that equipment. If careful attention is not paid to all aspects of the design and installation of the PV system, the PV-unique BOS and other BOS components will fail prematurely or need repairs long before the PV modules cease to produce energy. Such failures may reduce power output from the system or cause the system to quit working. More importantly, however, is the fact that some BOS (both PV-unique and other) failures may create safety hazards that could endanger human life or destroy property.

National testing laboratories such as Underwriters Laboratories (UL), ETL, and CSA have evaluated the safety of electrical PV equipment against standards published by UL. Tested and listed PV equipment in all categories (except for batteries) is currently available, and the use of this listed equipment gives some assurance that basic safety and to some extent performance (e.g., inverter power output, charge controller maximum currents) requirements have been met.

Today, it is possible to purchase an entire PV system (utility-interactive, stand-alone, hybrid, or combination) that consists of mainly listed components (excepting batteries). If these components are properly integrated into an appropriately designed system and carefully installed following the manufacturer's instructions and the requirements of the *National Electrical Code* (*NEC*) and local codes, the system has an excellent probability of providing safe, long-lasting, and durable electrical power with minimal operations and maintenance (O&M) support. That O&M support would consist mainly of maintenance and replacement of batteries (if installed) and the engine-driven generator (if installed). Numerous examples of these systems are available. Owners enjoy the energy output of these systems for years with little attention paid to the system.

These systems have usually been permitted (where required), installed by qualified people, and inspected by a local electrical inspector (where required). Those qualified installers follow the detailed instructions provided by the PV and BOS equipment manufacturers, use the requirements of the *NEC* as a minimum set of safety and installation guidelines, and use their significant experience to deliver high-quality systems. Those years of experience may have been obtained by installing PV systems, but generally the better installers have years of experience as practicing electricians with added years of experience or training on PV systems. Teams consisting of electricians and PV system designers have also shown to have the necessary collective qualifications to make these superlative installations.

The system quality is further improved by involvement with the local electrical inspector, who, if knowledgeable on PV systems, may provide additional quality guidance. These systems are typified by compliance with all national and local electrical and building codes, good workmanship normally seen only in commercial electrical installations, and informed people involved at all stages in the process including the owner, the designer, the installer, and the inspector.

3.4. Issues with PV Installations

This project has demonstrated the shortcomings of PV system installations in the SMUD territory. The poor safety, performance, and durability record of these systems may be traced to a number of areas.

Manufacturers of PV equipment (modules, inverters, charge controllers, and PV-unique BOS) have been known to sell equipment into the market that has not been adequately tested for installation ease, interface compatibility, performance, and long-term reliability. The customers who receive this equipment end up as alpha or beta testers for the manufacturers and the vendor/installers take the blame for less-than-adequate performance. Even equipment that has passed the basic safety standards established by the listing process may not perform properly. Aside from UL Safety Standards (UL 2001; UL 2002) and IEEE Standard 1262 for PV modules (IEEE 1995), no performance and reliability tests, or certifying agencies for PV inverters and charge controllers exist. These entities are developing such standards and implementing certifying procedures. Manufacturers are also supplying varying levels of installation instructions and installation hardware with their products that range from detailed to simple. In some cases, companies who are selling "systems" or kits of equipment are unwilling to acknowledge or take responsibility for failures of components in the system.

A second causative factor, and probably more important from a system safety and failure point-of-view, is improper design and installation (Schultze 2001). The requirements for the proper design and installation of electrical power equipment and systems have been well understood for decades. Unfortunately, design and installation instructions, manuals, and codes are not always followed when PV systems are installed. Equipment from other sources (plumbing, construction, automotive, marine, etc.) has been substituted (knowingly and unknowingly) for the proper electrical equipment. Sometimes, inexperienced people design and install PV systems. This is further complicated when the manufacturer's literature does not provide adequate information or simply states "install according to the code." In many areas, solar hot water and weatherization contractors are certified or grandfathered as PV installers after only one to four days of PV installation training and passing "minimal" certification exams. Some contractors are not installing systems in compliance with the *NEC,* and some of these systems are not functional initially, fail prematurely, or do not deliver expected or designed performance. Since the *NEC* and local codes are legislated into law by the local jurisdictions, any violation of the requirements of these codes is unlawful. But more importantly, code violations will generally result in safety hazards immediately, in the near term, or in subsequent years.

Some utility-interactive systems may lack discernable indicators to show the system's functionality. Systems may produce less energy than predicted by operating continuously at lower-than-designed power levels or by operating intermittently. Stand-alone and battery-backed up utility-interactive systems may experience premature battery failures due to improper charge regulation.

Inspections of these systems have revealed problems with some of the installations (Brooks 2000). Poor workmanship that has not met minimal residential construction requirements has been evident. Electrical equipment from questionable sources (for electrical power systems) has been used, including unlisted electronic parts and cables, overcurrent protection, and switchgear not listed or intended for building power systems:

- Unlisted PV equipment that is not compatible with other listed equipment.
- Overcurrent devices and conductors with improper ratings.
- AC devices used in DC circuits.
- Conductors not installed in conduits where required.
- Hardware-store nuts and bolts used to make improper high-current electrical connections.
- Terminals left exposed, creating electrical shock and fire hazards.
- Battery fires and explosions due to improper installation and maintenance.

In addition, conductors have been subject to early failure (months or years rather than decades) because the wrong types of conductors were selected, they were improperly sized, or they were improperly installed.

While a few of these problem systems performed initially at full capacity, and some of them performed initially at less than full capacity, the long term safety, reliability, and performance was compromised. Attention to detail in the design and installation process is key to providing lasting performance. PV systems include multiple parts that all have important functions. If these parts are not installed properly, initial output can suffer and long-term performance is reduced.

3.5. Better Performance and Safety Can Be Achieved

PV systems can be designed and installed in a way that delivers high levels of satisfaction. The manufacturers of electronic equipment (inverters and charge controllers) must develop performance and reliability standards, and fully test and evaluate their products against those standards, as do the PV module manufacturers, before releasing them for sale. All PV equipment manufacturers must "close the loop" with PV system designers and installers to ensure their products can be installed safely and reliably in a wide range of environments. Manufacturers of inverters and charge controllers should participate in a national certification program that will allow PV system designers and installers to know what to expect when using these components.

Sufficiently detailed instructions are critical in pre-engineered systems. Few BOS companies provide the level of detail required for even seasoned installers. Although general and specific requirements of the *NEC* and any local codes may not be essential, the interface details unique to each product must be included. All module manufacturers should publish performance data at Normal Operating Cell Temperatures (NOCT) in addition to the Standard Test Condition (STC) data to allow for more realistic performance assessments to be made (Brooks 2001). Good system documentation has many benefits for both experienced and inexperienced installers. Poor documentation adds unnecessary time and confusion for experienced installers and adds to the high probability that inexperienced installers will make major mistakes.

PV designers and installers must take advantage of all available design and installation material. The *NEC* and *NEC Handbook* provide installation guidance consistent with the requirements for other electrical power systems, and they describe many of the unique requirements of PV systems. Supplemental information on the proper design and installation of PV systems is published by IEEE (IEEE 1998), government agencies like Sandia National Laboratories (Wiles 2001) and the California Energy Commission (CEC 2001), and in popular publications like *Home Power Magazine*.

Any person installing PV systems should be well trained and experienced in installing other electrical power systems. It takes three to five years of intensive training and testing for an apprentice electrician to be certified as a journeyman electrician. A PV installer deals with the same voltage and current levels as an electrician. Anyone installing PV systems should have a working knowledge of at least the first four chapters and Chapter 9 of the *NEC* in addition to Article 690 on PV systems. The PV installer should be trained, experienced, and certified in the same manner as other professionals who install residential electrical power systems (typically a two-year program is the minimum requirement for residential electrical installers). Electrical inspectors should receive more intensive training on the inspection of PV systems. In any given location, PV installations should be inspected to the same degree that retrofit or new residential electrical systems are inspected. Although non-residential PV systems, such as water pumping systems, do not present the same safety hazards as residential systems do, the same degree of professionalism in design and installation must also be applied to these systems.

PV designers and installers must learn to evaluate PV system performance to determine if the newly installed system is operating properly and if the older system is maintaining proper levels of safety and performance. This is one of the most significant immediate needs of the new subsidized grid-connected markets. Since one of the main goals of grid-connected systems is the reduction of purchased energy from the electricity provider, the quantity of energy produced by the PV system is critically important. Most field installers are unable or unwilling to provide customers with this information, which causes them to constantly wonder if the system is working properly. Without an adequate energy performance estimate and energy metering, customers are unable to judge how well their systems are working and whether they are in need of maintenance.

3.6. Achieving Higher Quality PV Systems with Current SMUD Staff

At the present time, SMUD has three very knowledgeable employees who are intimately familiar with PV systems—how they are designed, how they should be installed, how they operate, and how they are maintained. These employees are Bob Puliz, Guy Miller, and Ken Miller, electrical technicians in the PV Section of the Maintenance Division. Unfortunately, the only interface that these well-qualified people have with the procurement and installation of PV systems at SMUD is that they are called to analyze and repair problems that occur on installed systems. They have no responsibilities at the front-end of the PV system procurement cycle. The suggested procedures presented will involve these three people (SMUD PV Experts) early in the procurement cycle for SMUD-owned and operated PV systems, and will also involve them in the evolution of the program of SMUD customer-owned systems installed by SMUD-recommended contractors.

3.7. SMUD-Owned Systems

The following procedures have been successfully used by other municipal utilities to acquire safe, well-performing, reliable PV systems:

1. Develop a stringent technical specification. While not containing significant amounts of useless *boilerplate*, it should contain the necessary contractual requirements to achieve the desired quality PV systems. A suggested outline of such a specification is listed in Appendix C. The SMUD PV Experts mentioned above should initially review the specification to tailor it to general SMUD requirements and then review it again before each procurement to adjust the requirements for each particular system.
2. Require all bidders to include a Design Package with their system showing full details (both mechanical and electrical) of the proposed design and the calculations leading to that design.
3. Evaluate the Design Packages from each bidder. SMUD PV Experts and other appropriate SMUD personnel (i.e., mechanical, electrical, and civil engineers) should determine how well the proposed systems meet the technical specifications.
4. Require an updated Design Package after the final vendor is selected. Submissions should be subject to review and approval before any authorization to proceed is given. Qualified people will again review this Design Package for code compliance and compliance with other contractual requirements. Any changes necessary to meet contractual or code requirements will be made by the vendor before SMUD approval is given to purchase and install materials.
5. Inspect and test the system after installation and before it is commissioned and turned over to SMUD. SMUD PV Experts (or a designated third party) will check for compliance with all appropriate electrical and mechanical codes and proper operation. All non-compliant items should be corrected before the system is accepted by SMUD. Performance testing is suggested as part of the acceptance tests and inspections.

3.8. Customer-Owned Systems

SMUD is planning to provide a list of “qualified” contractors to customers who wish to purchase their own PV systems and have them connected to the SMUD grid. By providing this list of “qualified” contractors, SMUD may assume some liability if PV systems installed by these contractors fail, prove unsafe, or perform poorly. Also, the safety of SMUD line maintenance personnel may be compromised if the systems are not properly designed and installed.

It has been noted that even supposedly well-qualified PV installers (those with past PV experience as SMUD employees) have recently installed non-code-compliant, unsafe SMUD-owned PV systems.

In other jurisdictions (e.g., New Mexico and New Jersey), a fully qualified inspector employed by the utility makes a full examination and inspection of the entire PV system before the customer is allowed to connect it to the utility.

The following suggestions could increase the likelihood that PV installers listed on the SMUD “Qualified Contractors” List are indeed capable of installing a safe, code-compliant PV system with the good workmanship required to ensure reliability and long life. The suggestions will also help minimize SMUD liability if the system should fail to perform to expectations:

1. The PV vendor/installer must use licensed electricians who are familiar with the requirements of the *NEC* and local electrical codes.
2. The PV vendor/installer must have at least one North American Board of Certified Energy Practitioners (NABCEP) certified PV installer on staff.
3. The PV vendor/installer must have all personnel actually designing and installing PV systems attend a two-day class sponsored by SMUD. The SMUD PV Experts will review the subject matter and course outline to ensure past and current PV system problems SMUD has experienced are covered in the class. They may attend one or more classes to provide real-time feedback to the class attendees. The class should cover some of the PV-unique code requirements and good workmanship requirements, and present numerous examples of poorly-installed SMUD PV systems (either by tour or pictures). The class will in no way be a substitute for the vendor using code-knowledgeable installers.
4. The PV vendor/installer will have the system permitted and inspected as required by the local jurisdiction and as required for any other equivalent electrical system (residential or commercial).
5. SMUD PV experts will fully inspect each PV system before it is interconnected and verify that it is producing nearly the rated output after interconnection. Code violations or workmanship problems will prevent the permanent interconnection to the SMUD distribution system. SMUD will notify the customer of any performance problems, and will report subsequent performance problems identified by the PV kWh meter readings and the PI analysis programs.

3.9. Summary

PV systems are electrical power systems. They should be designed and installed with the same level of care and professionalism that is used to install other electrical power systems. The system designs should be carried out following the equipment manufacturer's instructions and with full knowledge of the requirements of the *NEC*. A licensed person with experience installing similar PV systems or other electrical power systems should make the installation.

Outstanding, safe, reliable, durable, full-performance PV systems are being installed today that will continue to give many years of satisfactory performance with minimum maintenance. Well-qualified professionals are doing those installations. The entire PV industry must take steps to ensure all future PV installations meet the high standards that have been demonstrated. SMUD can facilitate this process by involving their most qualified people early in the project and by adopting the suggestions outlined above.

4.0 Residential PV System Field Tests

During the week of December 5, 2005, engineers from SWTDI inspected nine residential PV systems in the Sacramento area, assisted by SMUD PV service technician Ken Miller. The engineers performed different levels of tests on various systems, and recognized several as underperforming as a result of obvious shading. Below are the results of some of the system tests that illustrate a few of the recurring problems identified.

4.1. System 1

System 1 consists of 36 Siemens SP75 modules on two planes of east-facing roof connected to a Xantrex SunTie STXR2500UPG inverter. Initial inspection showed obvious shading from the large trees to the east (Figure 12).

Figure 12. System 1 array in two east-facing segments, shaded by trees

Photo Credit: SWTDI

The engineers inspected the inverter and measured the operating currents of the array's five strings. Table 4 presents the string currents measured under partially shaded conditions, plane of array irradiance at 350 W/m², ambient temperature of 13°C (55.4°F). Current mismatch among strings is probably due to some strings having different numbers of modules in parallel and also some strings being shaded.

Table 5. Operating currents of five strings on System 1

String 1	String 2	String 3	String 4	String 5
1.24 A	4.38 A	1.15 A	1.95 A	4.40 A

Source: Data collected by Ken Miller and SWTDI December 5, 2005 to December 12, 2005

The field team observed a poorly operating inverter during the string current measurements. The array voltage at maximum power was only 38 V_{dc}. The inverter was seeking maximum power on a recurring 20 second cycle. It began by operating the array near open circuit (79 V_{dc}). It then moved the operating point down in voltage to find maximum power more than a 10 second cycle (V_{mp}, in this case was 38 V_{dc}). It remained at 38 V_{dc} for an additional 10 seconds, and then the cycle repeated. This inverter is in need of factory service. SMUD system inspection performed on April 13, 2003, indicated that V_{mp} for this array was measured to be 63.4 V_{dc} and no mention of this "seeking" was noted.

4.2. System 2

System 2 consists of 20 Siemens SP75 modules on a single south-facing roof connected to a Xantrex SunTie STXR2500UPG inverter. Initial inspection showed no shading from any trees (Figure 13). Under irradiance of 710 W/m², ambient temperature of 16°C (60.8°F), the inverter was producing only 333 W_{ac}, or about 50% of expected output.

Figure 13. System 2 array

Photo Credit: SWTDI

The engineers removed the inverter cover and inspected the inverter. The array is wired with three fused strings. Fuse 1 was found to be blown (Figure 14). The failed fuse was replaced with the fuse from the unused String 4 circuit.

At the same time, opening a combiner box on the roof revealed that a wire nut had failed inside. Figure 15 shows the failed wire nut as it was found. This wire nut, failing as it did against the grounding lug, may have contributed to the blown fuse for this circuit. The failed wire nut was cut off and replaced.

Following replacement of the wire nut and fuse, array output was measured at 710 W_{ac}.

Figure 14. System 2 inverter with blown fuse indicated
Photo Credit: SWTDI

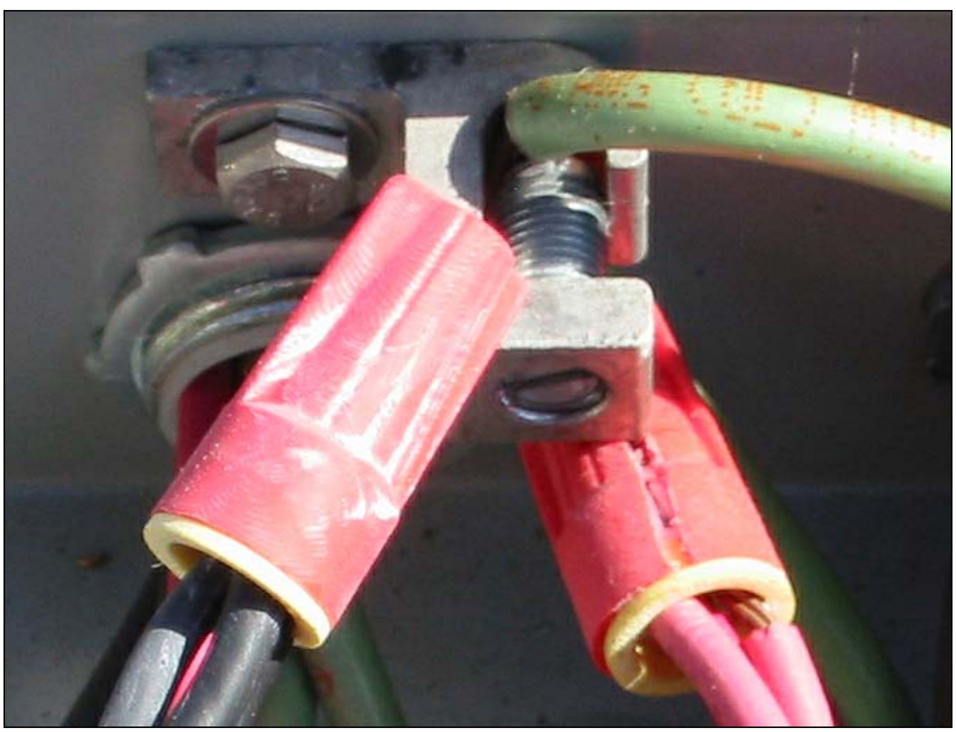

Figure 15. System 2 combiner box interior showing failed wire nut
Photo Credit: SWTDI

4.3. System 3

System 3 consists of 56 Dunasolar EPV-40 modules on two west-facing roofs connected to an SMA Sunny Boy 2500U inverter. Initial inspection showed little shading from trees (Figure 16). Under irradiance of 640 W/m^2, ambient temperature of 16°C (61°F), the inverter produced 699 W_{ac}, which is less than expected.

Figure 16. System 3 array mounted on two west-facing rooftops
Photo Credit: SWTDI

The string fuses were tested and all found to be good. Inspection of the modules showed many had delaminated in the area around the module edges and in a square pattern opposite the wiring block (Figure 17). Delamination of this nature is unusual.

Figure 17. System 3 module delamination opposite the module wiring block
Photo Credit: SWTDI

4.4. System 4

System 4 consists of 48 Dunasolar EPV-40 modules on two non-planar roofs: one facing south, the other west. The array is connected to a Xantrex STXR 2500 UPG inverter. Initial inspection showed significant shading from trees located to the south (in the neighbor's yard) and west (in the homeowner's yard). Array and inverter performance were not measured because of heavy clouds at the time of testing.

Visual inspection revealed this to be the most delaminated array visited. The worst module was visible from the ground. Figure 18 shows this cracked module with its photovoltaic material weathered away over much of the glass. However, many of the modules with intact glass showed serious delamination around module borders and, again, in the PV material opposite to the module wiring block (Figure 19). Delamination allows for water ingress and can accelerate module failure.

Figure 18. System 4 cracked and weathered module

Photo Credit: SWTDI

In addition to the delaminated modules, the field team found three failed wire nuts in one of the roof combiner boxes. Figure 20 shows the three failed wire nuts in the roof combiner box at System 4. In the photo, the two wire nuts at the bottom are seen to have split more completely than the third, which appears to be beginning this process.

Figure 19. System 4 showing widespread delamination
Photo Credit: SWTDI

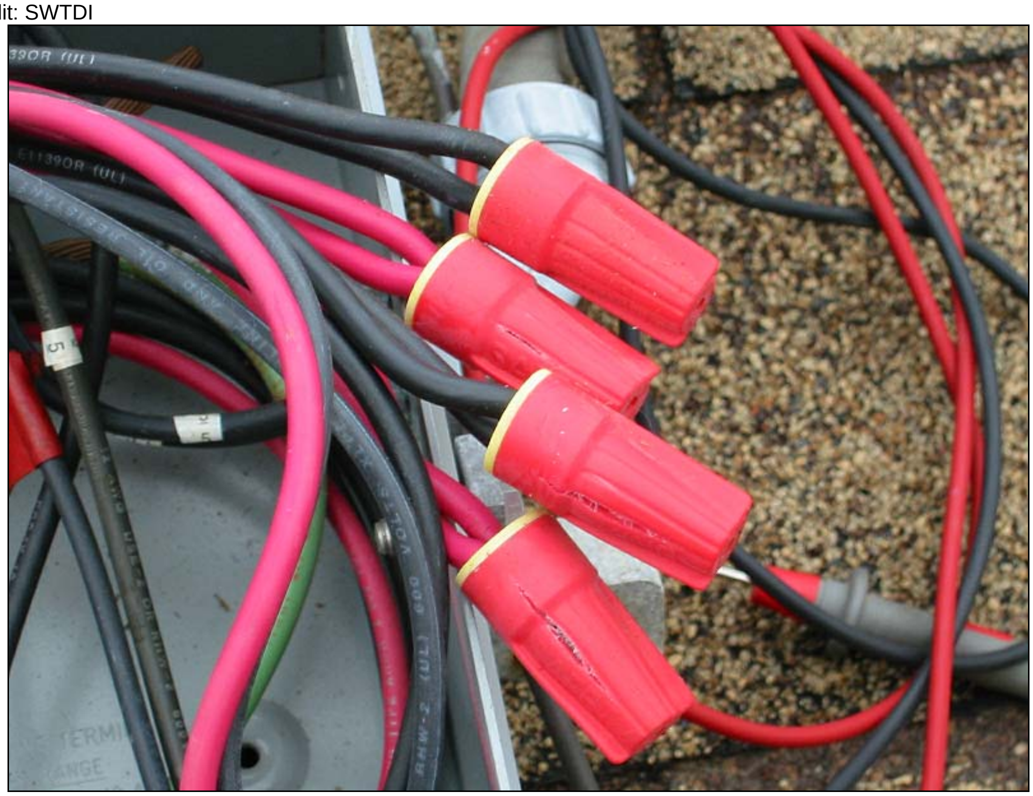

Figure 20. System 4 combiner box with three failed wire nuts
Photo Credit: SWTDI

4.5. Recommendations and Conclusions

Testing this small number of systems uncovered several recurring problems.

4.5.1. Shading

Sacramento is a verdant area with numerous species of deciduous and evergreen trees. Tree shading is the most common reason for poor performance found among the PV systems tested. However, shading by sources other than trees was also observed. One system was installed so that it is shaded for several hours every afternoon by a large chimney (Figure 24). The effects of shading on system production are difficult to estimate by observation alone. The reduction in array output is a function of how the array is wired and which modules and strings are completely or partially shaded at a given time.

4.5.2. Inverter-related Problems

Poor inverter performance can be difficult to diagnose and, in some cases, may actually be a result of array problems (e.g., degraded modules). The inverters in question were all Xantrex SunTie STXR2500. Product literature for this inverter states that the MPPT voltage range is 44 to 85 V, with full power attainable only when input voltage is between 52 and 75 V. However, several units were measured at DC operating voltages of 38 to 40 V. This may represent an MPPT problem or be the result of severely degraded PV array output. Regardless, inverter efficiency (and system AC output) at this extreme input voltage is reduced.

One STXR2500 was recognizably in need of repair. The unit operated on a recurring 20-second cycle. At the start of the cycle, it took 10 seconds to slowly track the array voltage from open circuit (79 V_{dc}) to its perceived maximum power value (38 to 39 V_{dc}). It then operated there for 10 seconds before returning to V_{oc} and repeating the cycle.

4.5.3. PV Module Problems

Many problems were observed with one PV module type: Dunasolar EPV-40. Delamination was found in modules from several arrays. Particularly susceptible was the area opposite the module wiring block. Performance of all Dunasolar arrays was markedly less than nameplate.

4.5.4. Wiring Problems

Numerous wire nuts from several systems had failed within rooftop string combiner boxes. The wire nuts at issue are of the type filled with a dielectric paste to provide a reliable wet rating (Connector series number 602, King Safety Products, with more information in Appendix D). During these tests, two systems were found with failed wire nuts. Review of notes taken during testing done by SWTDI in 2003 showed a failed wire nut was found at that time. Wire nuts are ubiquitous. Potential reasons for failures may include:

1. Use of wire nuts with improper temperature rating.
2. Improper installation procedure (e.g., over twisted).
3. Product failure due to manufacturing defect.

4.6. Recommendations

The number of systems tested was not sufficient for statistical analyses and, clearly, only systems known to be poor performers were examined. However, the recurrence of specific problems at different locations indicates the presence of issues that need to be addressed.

Shading by trees is a problem that cannot be solved easily. Many SMUD PV homeowners are well intentioned and interested in obtaining the best performance from their systems. If shading is explained to them, some will choose to trim trees, where possible. Others will not, or where trees are in neighboring yards, cannot. Solar access rights may also be an issue.

Figure 21. Examples of shading by trees (left) and permanent structures (right)

Photo Credit: SWTDI

SMUD should develop a short pamphlet to explain the effects of shading to its PV customers (if this has not been done already). This pamphlet could be sent to all customers or just the PV homes. Many homeowners with severely shaded PV arrays told us they knew their systems were producing less than in the past but did not recognize this obvious cause.

The degrading performance of the Dunasolar EPV-40 modules will likely become worse and more prevalent with time. As production from these arrays declines, PI values will continue to drop and recurring alerts from permanently low PI values will be common. The research team recommends creating a program to identify and mark known problem systems in the SMUD PV system database. This can be done for systems known to be severely degraded that are no longer reasonable candidates for accurate PI assessment. Once so marked, the nameplate ratings for such systems can be manually adjusted downward. Lowering the nameplate ratings will result in an expectation of less energy from these systems and eliminate recurring low PI alerts. Beyond PI concerns, SMUD’s policy of technical support for these systems will need to be defined (if it is not already) to include the anticipation of this trend in performance degradation. The warranty terms for these modules is not known, but is of critical importance.

The Xantrex STXR2500 inverters have all been through the Xantrex upgrade program of 2003, but unless SMUD negotiated a separate arrangement with Xantrex, the original warranty period of two years has elapsed. At least one unit was in obvious need of factory service. SMUD should make a program to identify and review the PI data from all STXR2500 systems. Where possible, PV technicians should conduct field follow-up to locate others not operating properly and in need of service.

The last recommendation addresses the wire nuts. The research team contacted the manufacturer, and a technical sales representative needed to search company archives to obtain data sheets for these now discontinued items (included in Appendix D). The representative gave no reason for the discontinuation of this series. To the extent possible, SMUD should contact the installer of these PV systems and find out when and where these wire nuts were purchased. This information should be brought to the manufacturer to see if these were known defective products or if similar failures of these products have been observed elsewhere. At a minimum, SMUD should obtain recommendations for repair or replacement of these products.

For the existing systems, it is reasonable to expect that many of the component problems, such as module degradation and failing wire nuts, will grow more widespread over time. The most critical issue SMUD must address is to identify any safety concerns these problems may present. Following that, SMUD must develop and adopt clear policies covering repair, replacement, or abandonment of these failing systems (as they choose) and these policies should be fully presented to the PV customers.

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Glossary

BOS	Balance-of-Systems
CEC	California Energy Commission
CSA	Canadian Standards Association
Diff	Diffuse Irradiance
DNI	Direct Normal Irradiance
ETL	ETL SEMKO division of Intertek is an organization which tests, certifies, and inspects products for global market access.
IEEE	Institute of Institute of Electrical and Electronics Engineers
IT	Information Technology
kWh	kilowatt hours
MPPT	Maximum Power Point Tracking
NEC	National Electrical Code
NMSU	New Mexico State University
NOCT	Normal Operating Cell Temperatures
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
PI	Performance Index
PIER	Public Interest Energy Research
POA	Plane of Array Irradiance
PV	Photovoltaic
PVII	PV Pioneer II Residential Program
RD&D	Research, Development, and Demonstration
ReGen	SMUD Renewable Generation Research program
SAP	Resource planning software
SMUD	Sacramento Municipal Utility District
SMUD PI	The software program created for SMUD to calculate the PI of an array
SNL	Sandia National Laboratories
STC	Standard Test Condition
SWTDI	Southwest Technology Development Institute
UL	Underwriters Laboratories
U.S. DOE	U.S. Department of Energy
V_{mp}	Voltage to find maximum power over a 10 second cycle
W	Watt
Wh	Watt-hour

Appendix A

NREL SOLPOS Documentation

NREL's SOLPOS 2.0: Documentation

SOLPOS.C

Distributed by the National Renewable Energy Laboratory
Center for Renewable Energy Resources
Renewable Resource Data Center
February 2000

NOTICE

This C function calculates the apparent solar position and intensity (theoretical maximum solar energy) based on the date, time, and location on Earth. The software has been tested on a variety of platforms, but as noted above, is not guaranteed to work on yours. It is provided here as a convenience.

This document provides only a general overview of the software functionality. The accompanying sample program soltest.c provides additional information by example on how the function is set up and called from an application program. That program serves as the only tutorial for the use of S_solpos.

The module contains three functions:

S_solpos	Performs calculations
S_init	Initializes S_solpos
S_decode	Decodes the return value from S_solpos

To obtain references for the algorithms see the References section below. Comments in the source code specify references for each function.

======================================

S_solpos (computes solar position and intensity from time and place)

INPUTS: (via posdata struct defined in solpos.h) year, daynum, hour, minute, second, latitude, longitude, timezone, interval

OPTIONAL: (via posdata struct) month, day, press, temp, tilt, aspect, function

OUTPUTS: EVERY variable in the struct posdata (defined in solpos.h)

S_init (optional initialization for all input parameters in the posdata struct)

INPUTS: struct posdata*

OUTPUTS: struct posdata*

Initializes the required S_solpos INPUTS above to out-of-bounds conditions, forcing the user to supply the parameters; initializes the OPTIONAL S_solpos inputs above to nominal values. See listing below for default values provided by S_init.

S_decode (optional utility for decoding the S_solpos return code)

INPUTS: long int S_solpos return value, struct posdata*

OUTOUTS: Text to stderr

Alphabetical list of common variables

The I/O column contains a letter code:

I: INPUT variable

O: OUTPUT variable

T: TRANSITIONAL variable used in the algorithm, of interest only to the solar radiation modelers and available to you because you may be one of them.

The FUNCTION column indicates which sub-function within solpos must be switched on using the "function" parameter to calculate the target output variable. All function codes are defined in the solpos.h file. The default S_ALL mask calculates all output variables. Multiple function masks may be ORed to create a composite function switch. For example, (S_TST | S_SBCF) will force the calculation of the shadow band correction factor as well as all variables required for S_TST (true solar time). Specifying only the functions necessary for required output variables might allow solpos to execute more quickly.

The S_DOY mask works as a toggle between the input date represented as a day of year number (daynum) and an input date represented by month and day of month. To set the switch (to use daynum input), the mask is ORed with the function variable; to clear the switch (to use month and day input), the mask is inverted and ANDed.

For example:

```
pdat->function |= S_DOY /* (sets daynum input) */

pdat->function &= ~S_DOY /* (sets month and day input) */
```

Whichever date form is used, S_solpos will calculate and return the variables(s) of the other form. See the sample program soltest.c for other examples.

VARIABLE	I/O	Function	Description
--------------------	-------	----------------	---
/**** INTEGERS ****/			
int day	I/O:	S_DOY	Day of month (May 27 = 27, etc.) Solpos will CALCULATE this by default, or will optionally require it as input depending on the setting of the S_DOY function switch.
int daynum	I/O:	S_DOY	Day number (day of year; Feb 1 = 32) Solpos REQUIRES this by default, but will optionally calculate it from year, month, and day depending on the setting of the S_DOY function switch.
int function	I:		Bit-oriented switch to choose function) for desired output.
int hour	I:		Hour of day, 0 — 24. (Time 24:00:00 is treated internally as time 00:00:00 of the following day.)
int interval	I:		Interval of a measurement period in seconds. Forces solpos to use the time and date from the interval midpoint. The INPUT time (hour, minute, and second) is assumed to be the END of the measurement interval.
int minute	I:		Minute of hour, 0 - 59.
int month	I/O:	S_DOY	Month number (Jan = 1, Feb = 2, etc.) Solpos will CALCULATE this by default or

			will optionally require it as input depending on the setting of the S_DOY function switch.
int second	I:		Second of minute, 0-59.
int year	I:		4-digit year (2-digit years NOT allowed)
/**** FLOATS ****/			
float amass	O:	S_AMASS	Relative optical air mass
float ampress	O:	S_AMASS	Pressure-corrected air mass
float aspect	I:		Azimuth of panel surface (direction it faces) N=0, E=90, S=180, W=270, DEFAULT = 180
float azim	O:	S_SOLAZM	Solar azimuth angle: N=0, E=90, S=180,W=270
float cosinc	O:	S_TILT	Cosine of solar incidence angle on panel
float coszen	O:	S_REFRAC	Cosine of refraction corrected solar zenith angle
float dayang	T:	S_GEOM	Day angle (daynum*360/year-length) degrees
float declin	T:	S_GEOM	Declination--zenith angle of solar noon at equator, degrees NORTH
float eclong	T:	S_GEOM	Ecliptic longitude, degrees
float ecobli	T:	S_GEOM	Obliquity of ecliptic
float ectime	T:	S_GEOM	Time of ecliptic calculations
float elevetr	O:	S_REFRAC	Solar elevation, no atmospheric correction (= ETR)
float elevref	O:	S_REFRAC	Solar elevation angle, degrees from horizon, refracted
float eqntim	T:	S_TST	Equation of time (TST - LMT), minutes
float erv	T:	S_GEOM	Earth radius vector(multiplied to solar constant)
float etr	O:	S_ETR	Extraterrestrial (top-of-atmosphere) W/sq m global horizontal solar irradiance
float etrn	O:	S_ETR	Extraterrestrial (top-of-atmosphere) W/sq m direct normal solar irradiance
float etrtilt	O:	S_TILT	Extraterrestrial (top-of-atmosphere) W/sq m global irradiance on a tilted surface
float gmst	T:	S_GEOM	Greenwich mean sidereal time, hours
float hrang	T:	S_GEOM	Hour angle--hour of sun from solar noon degrees WEST
float julday	T:	S_GEOM	Julian Day of 1 JAN 2000 minus 2,400,000 days (in order to regain single precision)
float latitude	I:		Latitude, degrees north (south negative)
float longitude	I:		Longitude, degrees east (west negative)

float lmst	T:	S_GEOM	Local mean sidereal time, degrees
float mnanom	T:	S_GEOM	Mean anomaly, degrees
float mnlong	T:	S_GEOM	Mean longitude, degrees
float rascen	T:	S_GEOM	Right ascension, degrees
float press	I:		Surface pressure, millibars, used for refraction correction and ampress
float prime	O:	S_PRIME	Factor that normalizes Kt, Kn, etc.
float sbcf	O:	S_SBCF	Shadow-band correction factor
float sbwid	I:		Shadow-band width (cm)
float sbrad	I:		Shadow-band radius (cm)
float sbsky	I:		Shadow-band sky facto
float solcon	I:		Solar constant (NREL uses 1367 W/sq m)
float ssha	T:	S_SRHA	Sunset(/rise) hour angle, degrees
float sretr	O:	S_SRSS	Sunrise time, minutes from midnight, local, WITHOUT refraction
float ssetr	O:	S_SRSS	Sunset time, minutes from midnight, local, WITHOUT refraction
float temp	I:		Ambient dry-bulb temperature, degrees C, used for refraction correction
float tilt	I:		Degrees tilt from horizontal of panel
float timezone	I:		Time zone, east (west negative). USA: Mountain = -7, Central = -6, etc.
float tst	T:	S_TST	True solar time, minutes from midnight
float tstfix	T:	S_TST	True solar time - local standard time
float unprime	O:	S_PRIME	Factor that denormalizes Kt', Kn', etc.
float utime	T:	S_GEOM	Universal (Greenwich) standard time
float zenetr	T:	S_ZENETR	Solar zenith angle, no atmospheric correction (= ETR)

All functions require the input parameters for time, date, latitude, longitude, time zone, and measurement interval. Some functions may require additional input parameters. The table below indicates with an "X" which, if any, additional input parameters are required for each function. After determining the output variables you require from the above list, make note of the required functions, then determine the required inputs from the table:

Function	**-------------------- Required Inputs ------------------**							
	solcon	press	sbwid	sbrad	sbsky	temp	tilt	aspect
S_AMASS	--	X	--	--	--	X	--	--
S_DOY	--	--	--	--	--	--	--	--
S_ETR	X	X	--	--	--	X	--	--
S_GEOM	--	--	--	--	--	--	--	--
S_REFRAC	--	X	--	--	--	X	--	--
S_PRIME	--	X	--	--	--	X	--	--

S_SOLAZM	--	--	--	--	--	--	--	--
S_SRSS	--	--	--	--	--	--	--	--
S_SSHA	--	--	--	--	--	--	--	--
S_SBCF	--	--	X	X	X	--	--	--
S_TILT	X	X	--	--	--	X	X	X
S_TST	--	--	--	--	--	--	--	--
S_ZENETR	--	--	--	--	--	--	--	--

The S_init function provides nominal values for the above inputs. The values are listed below (note that time and location variables are initialized out of bounds to force the user to provide valid inputs):

day	=	-99	/* undefined */
daynum	=	-999	/* undefined */
hour	=	-99	/* undefined */
minute	=	-99	/* undefined */
month	=	-99	/* undefined */
second	=	-99	/* undefined */
year	=	-99	/* undefined */
interval	=	0	/* instantaneous */
aspect	=	180.0	/* south */
latitude	=	-99.0	/* undefined */
longitude	=	-999.0	/* undefined */
press	=	1013.0	/* standard pressure */
solcon	=	1367.0	/* NREL uses this */
temp	=	15.0	/* Temperature of the standard atmosphere */
tilt	=	0.0	/* horizontal */
timezone	=	-99.0	/* undefined */
sbwid	=	7.6	/* Eppley shadowband */
sbrad	=	31.7	/* Eppley shadowband */
sbsky	=	0.04	/* Eppley shadowband */
function	=	S_ALL	/* calculate ALL output parameters */

Certain conditions exist during which some of the output variables are undefined or cannot be calculated. In these cases, the variables are returned with flag values indicating such. In other cases, the variables may return a realistic, though invalid, value. These variables and the flag values or invalid conditions are listed below:

amass	-1.0 at zenetr angles greater than 93.0 degrees
ampress	-1.0 at zenetr angles greater than 93.0 degrees<
azim	invalid at zenetr angle 0.0 or latitude +/-90.0 or at night
elevetr	limited to —9 degrees at night
etr	0.0 at night
etrn	0.0 at night
etrtilt	0.0 when cosinc is less than 0

prime	invalid at zenetr angles greater than 93.0 degrees
sretr	+/- 2999.0 during periods of 24 hour sunup or sundown
ssetr	+/- 2999.0 during periods of 24 hour sunup or sundown
ssha	invalid at the North and South Poles
unprime	invalid at zenetr angles greater than 93.0 degrees
zenetr	limited to 99.0 degrees at night

S_solpos returns a long integer error code. Each bit position in the long int represents an error in the range of a particular input parameter. The S_decode function in solpos.c examines the return code for errors and can be used as is or as a template for building an application-specific function.

The bit positions for each error are defined in solpos.h, and are listed below. (Bit positions are from least significant to most significant.)

```
/*        Code               Bit        Parameter          Range
          ===============    === ===================  =========   */
enum {S_YEAR_ERROR,      /*  0  year                   1950 - 2050   */
      S_MONTH_ERROR,     /*  1  month                     1 - 12     */
      S_DAY_ERROR,       /*  2  day-of-month              1 - 31     */
      S_DOY_ERROR,       /*  3  day-of-year               1 - 366    */
      S_HOUR_ERROR,      /*  4  hour                      0 - 24     */
      S_MINUTE_ERROR,    /*  5  minute                    0 - 59     */
      S_SECOND_ERROR,    /*  6  second                    0 - 59     */
      S_TZONE_ERROR,     /*  7  time zone               -12 - 12     */
      S_INTRVL_ERROR,    /*  8  interval (seconds)        0 - 28800  */
      S_LAT_ERROR,       /*  9  latitude                -90 - 90     */
      S_LON_ERROR,       /* 10  longitude              -180 - 180    */
      S_TEMP_ERROR,      /* 11  temperature (deg. C)   -100 - 100    */
      S_PRESS_ERROR,     /* 12  pressure (millibars)      0 - 2000   */
      S_TILT_ERROR,      /* 13  tilt                    -90 - 90     */
      S_ASPECT_ERROR,    /* 14  aspect                 -360 - 360    */
      S_SBWID_ERROR,     /* 15  shadow band width (cm)    1 - 100    */
      S_SBRAD_ERROR,     /* 16  shadow band radius (cm)   1 - 100    */
      S_SBSKY_ERROR};    /* 17  shadow band sky factor   -1 - 1      */
```

References

ASTRONOMICAL SOLAR POSITION:

Michalsky, J. 1988. The Astronomical Almanac's algorithm for approximate solar position (1950-2050). *Solar Energy* 40 (3), 227-235.

Michalsky, J. 1988. ERRATA: The astronomical almanac's algorithm for approximate solar position (1950-2050). *Solar Energy* 41 (1), 113.

DISTANCE FROM SUN TO EARTH

Spencer, J. W. 1971. Fourier series representation of the position of the sun. Search 2(5), 172. NOTE: This paper gives solar position algorithms as well, but the Michalsky/Almanac algorithm above is more accurate.

ATMOSPHERIC REFRACTION CORRECTION

Zimmerman, John C. 1981. Sun-pointing programs and their accuracy. *SAND81-0761*, Experimental Systems Operation Division 4721, Sandia National Laboratories, Albuquerque, New Mexico.

SHADOW BAND CORRECTION FACTOR

Drummond, A. J. 1956. A contribution to absolute pyrheliometry. *Q. J. R. Meteorol*. 2 Soc. 82, 481-493.

RELATIVE OPTICAL AIR MASS

Kasten, F. and Young, A. 1989. Revised optical air mass tables and approximation formula. *Applied Optics* 28 (22), 4735-4738.

RENORMALIZATION OF KT ("PRIME")

Perez, R., P. Ineichen, Seals, R., & Zelenka, A. 1990. Making full use of the clearness index for parameterizing hourly insolation conditions. *Solar Energy* 45 (2), 111-114.

SOLAR POSITION RELATIVE TO EARTH

Iqbal, M. 1983. An Introduction to Solar Radiation. *Academic Press*, NY. NOTE: The 1983 edition contains typographic errors in coefficients of some equations. Further, many algorithms given in this book are no longer the best. However, this book gives a complete overview of the issues and methods of measuring and modeling solar radiation.

Appendix B

SMUD PV Program Process Diagrams and Checklists

B1. Photovoltaic System Installation Process Diagram

B2. Customer Service and Service Notification

B3. Zero Meter Readings

B4. PV Statement Process

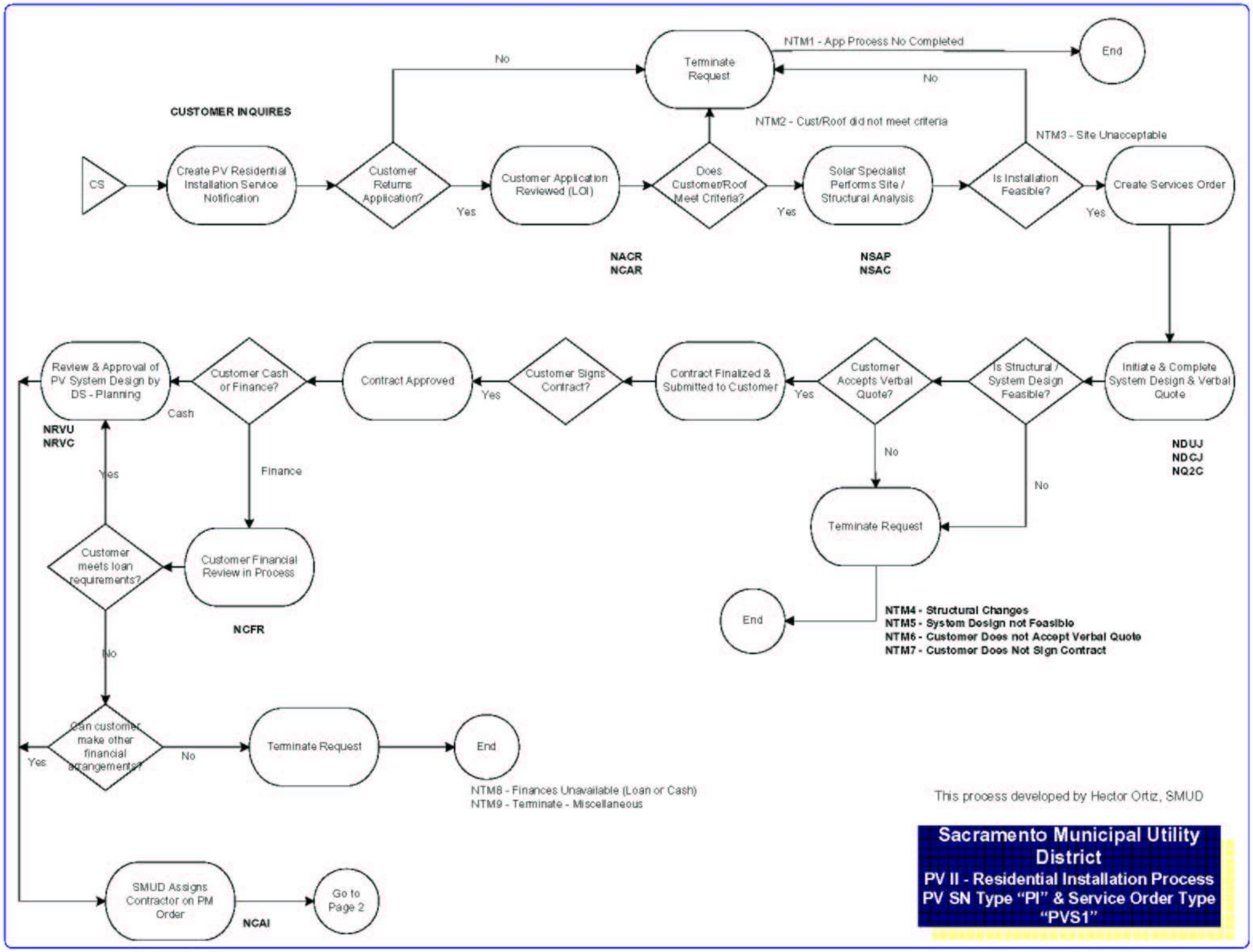
B5. PV Maintenance Process

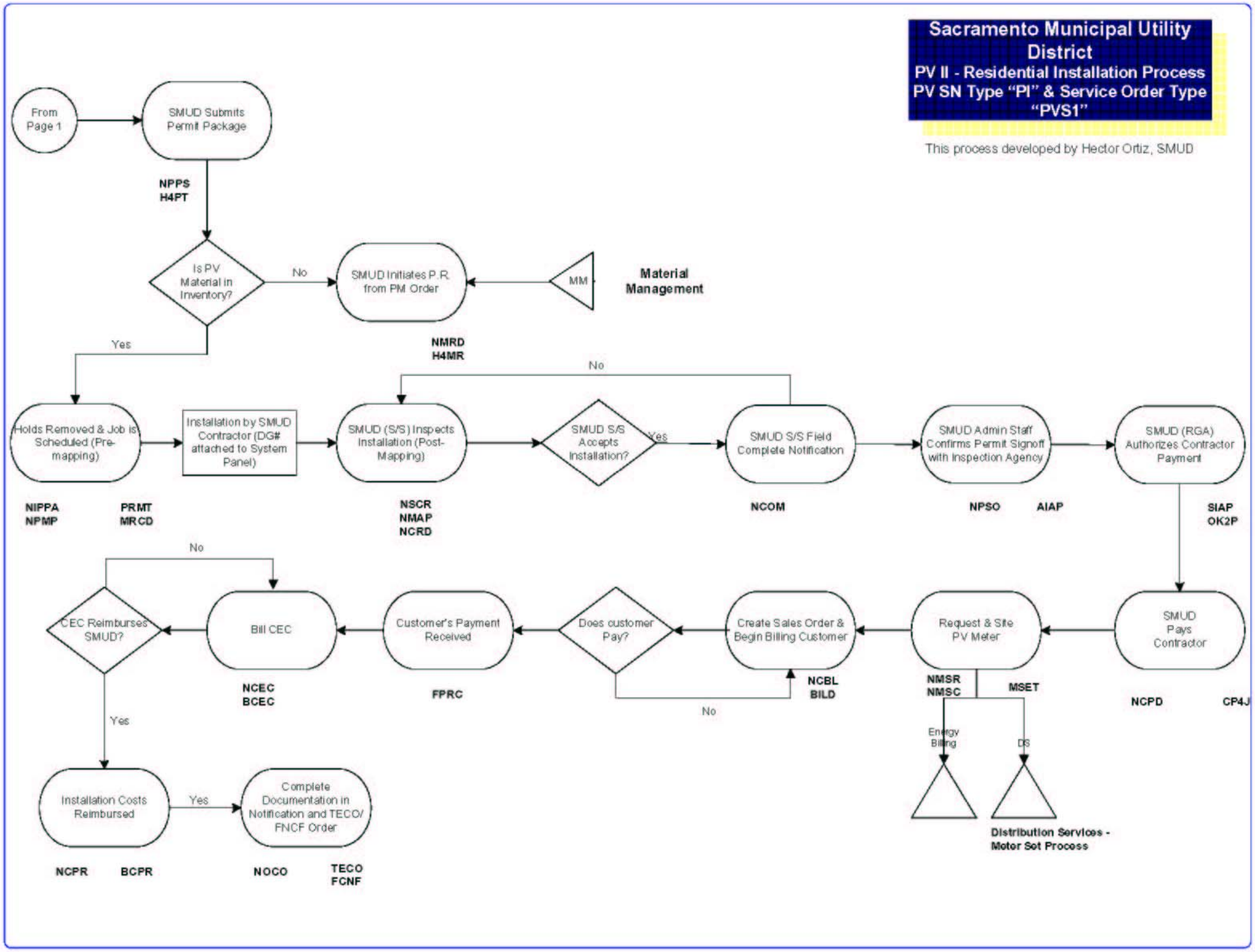
B6. Performance Indexing

B7. SMUD PV System Inspection and Commissioning

B8. SMUD PV System Inspection and Commissioning Checklist

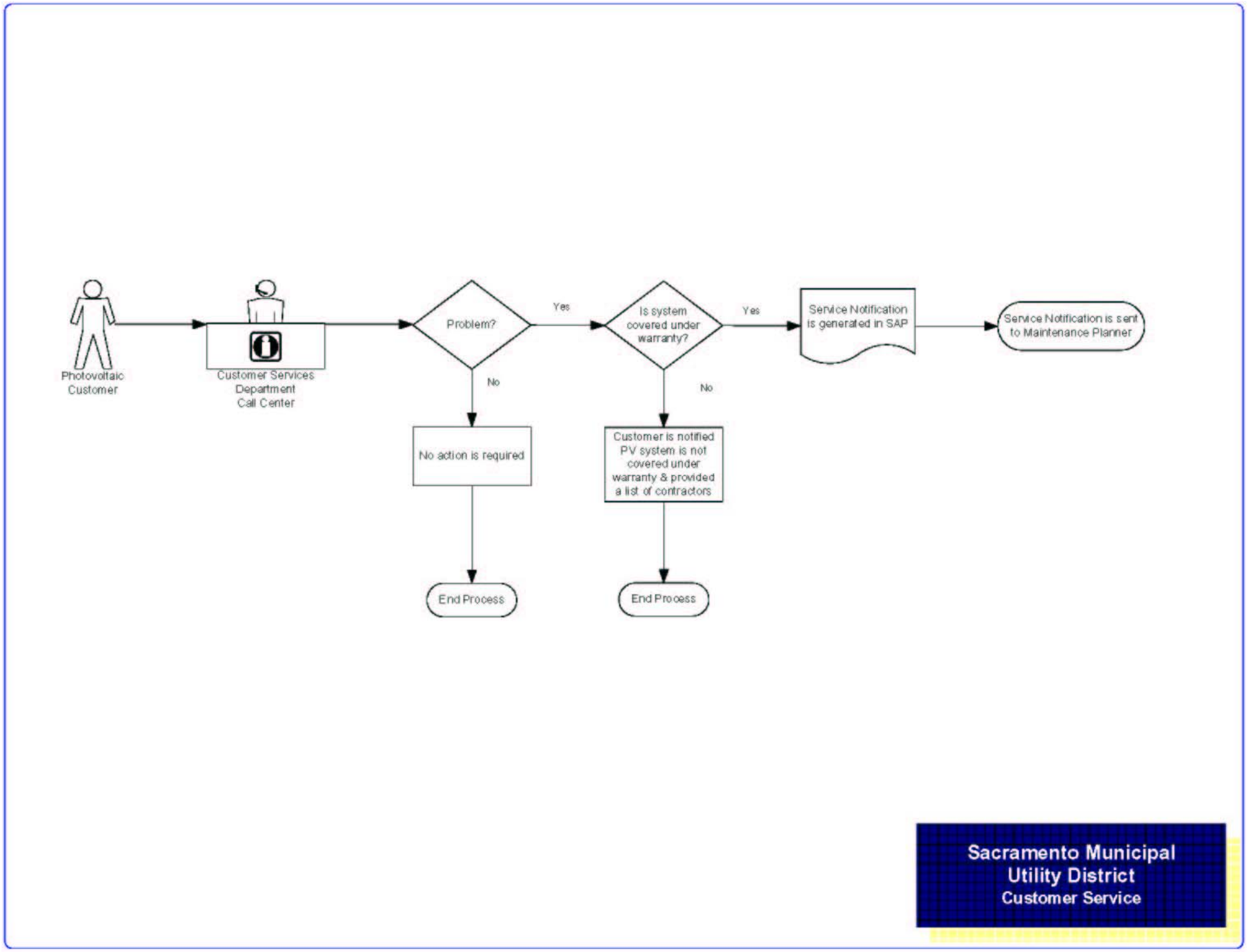
B1. Photovoltaic System Installation Process Diagram



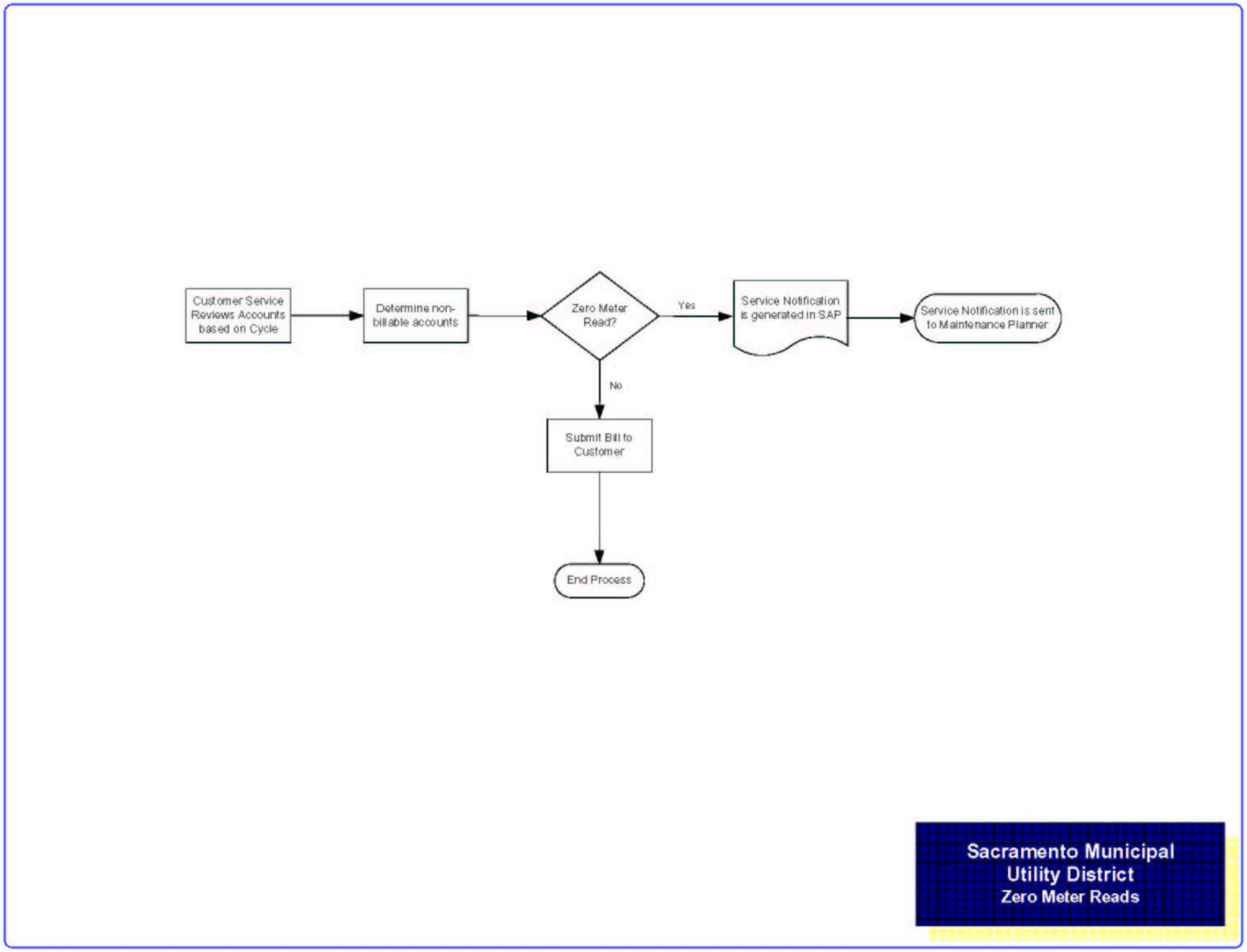


Sacramento Municipal Utility District
PV II - Residential Installation Process
PV SN Type "PI" & Service Order Type "PVS1"
This process developed by Hector Ortiz, SMUD
From Page 1
SMUD Submits Permit Package
NPPS
H4PT
Is PV Material in Inventory?
No
SMUD Initiates P.R. from PM Order
MM
Material Management
NMRD
H4MR
Yes
Holds Removed & Job is Scheduled (Pre-mapping)
NIPPA
NPMP
Installation by SMUD Contractor (DG# attached to System Panel)
PRMT
MRCD
SMUD (S/S) Inspects Installation (Post-Mapping)
NSCR
NMAP
NCRD
SMUD S/S Accepts Installation?
No
Yes
SMUD S/S Field Complete Notification
NCOM
SMUD Admin Staff Confirms Permit Signoff with Inspection Agency
NPSO
AIAP
SMUD (RGA) Authorizes Contractor Payment
SIAP
OK2P
SMUD Pays Contractor
NCPD
CP4J
Request & Set PV Meter
NMSR
NMSC
MSET
Energy Billing
DS
Distribution Services - Motor Set Process
Create Sales Order & Begin Billing Customer
NCBL
BILD
Does customer Pay?
No
Customer's Payment Received
FPRC
Bill CEC
NCEC
BCEC
CEC Reimburses SMUD?
No
Yes
Installation Costs Reimbursed
NCPR
BCPR
Yes
Complete Documentation in Notification and TECO/ FNCF Order
NOCO
TECO
FCNF

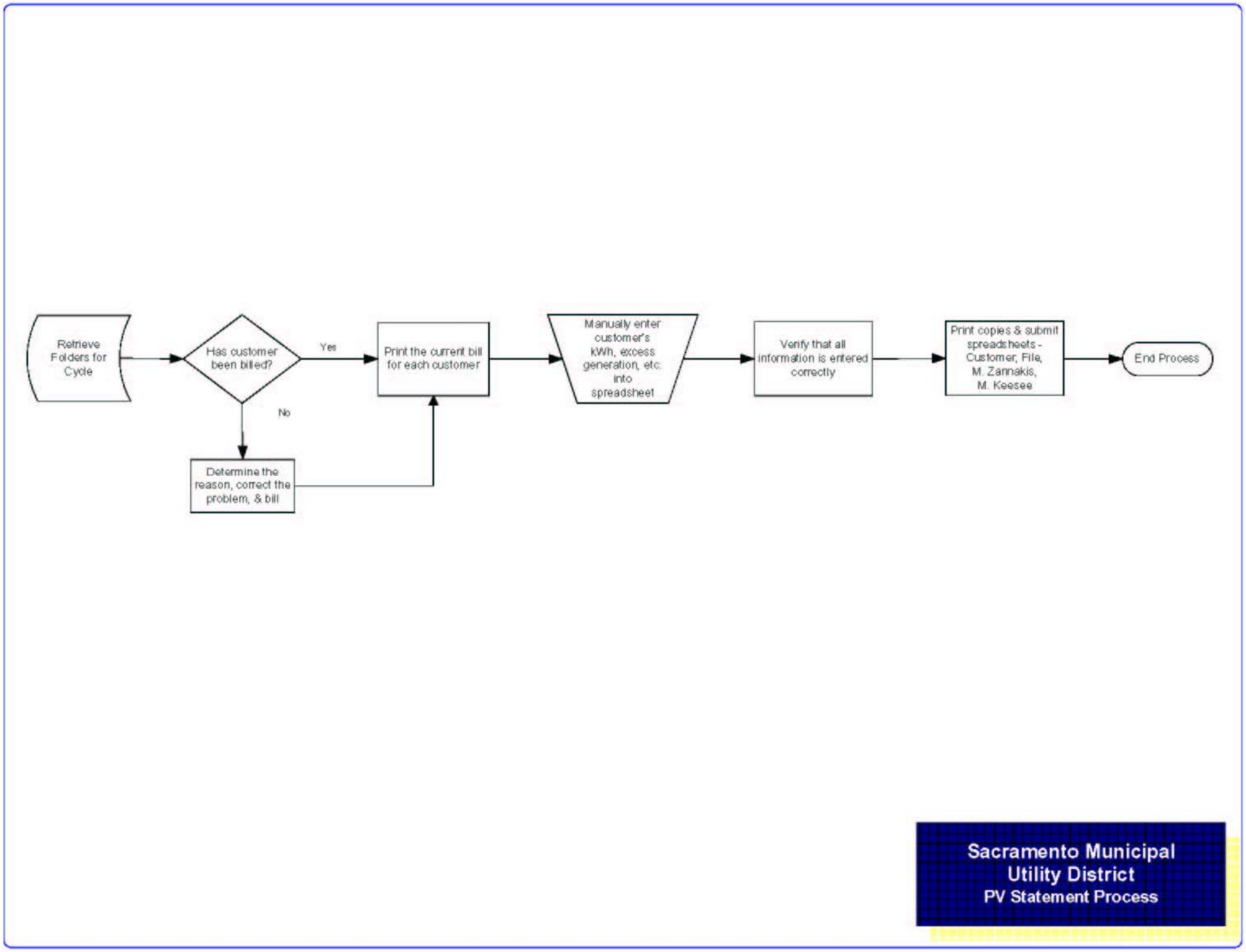
B2. Customer Service and Service Notification



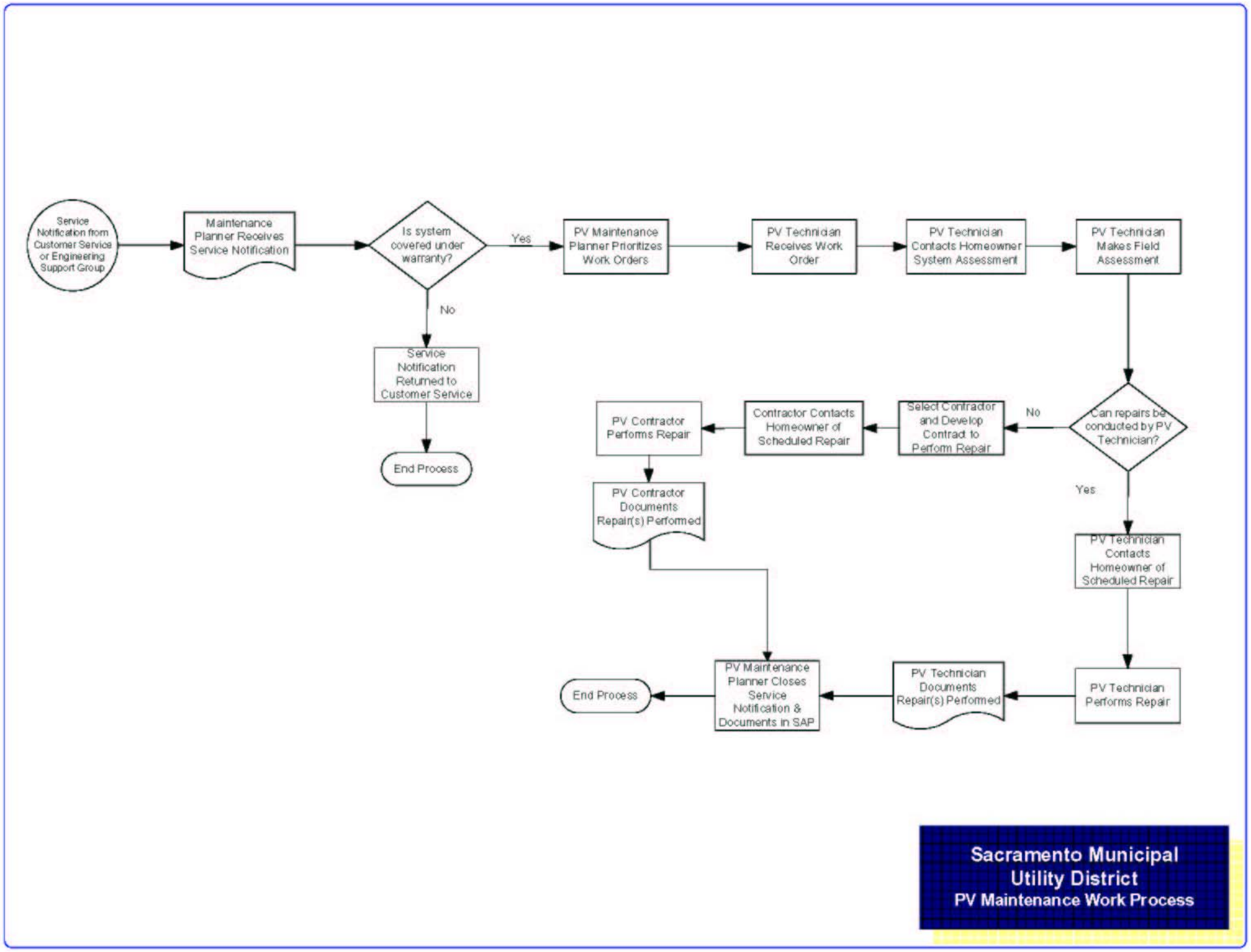
B3. Zero Meter Readings



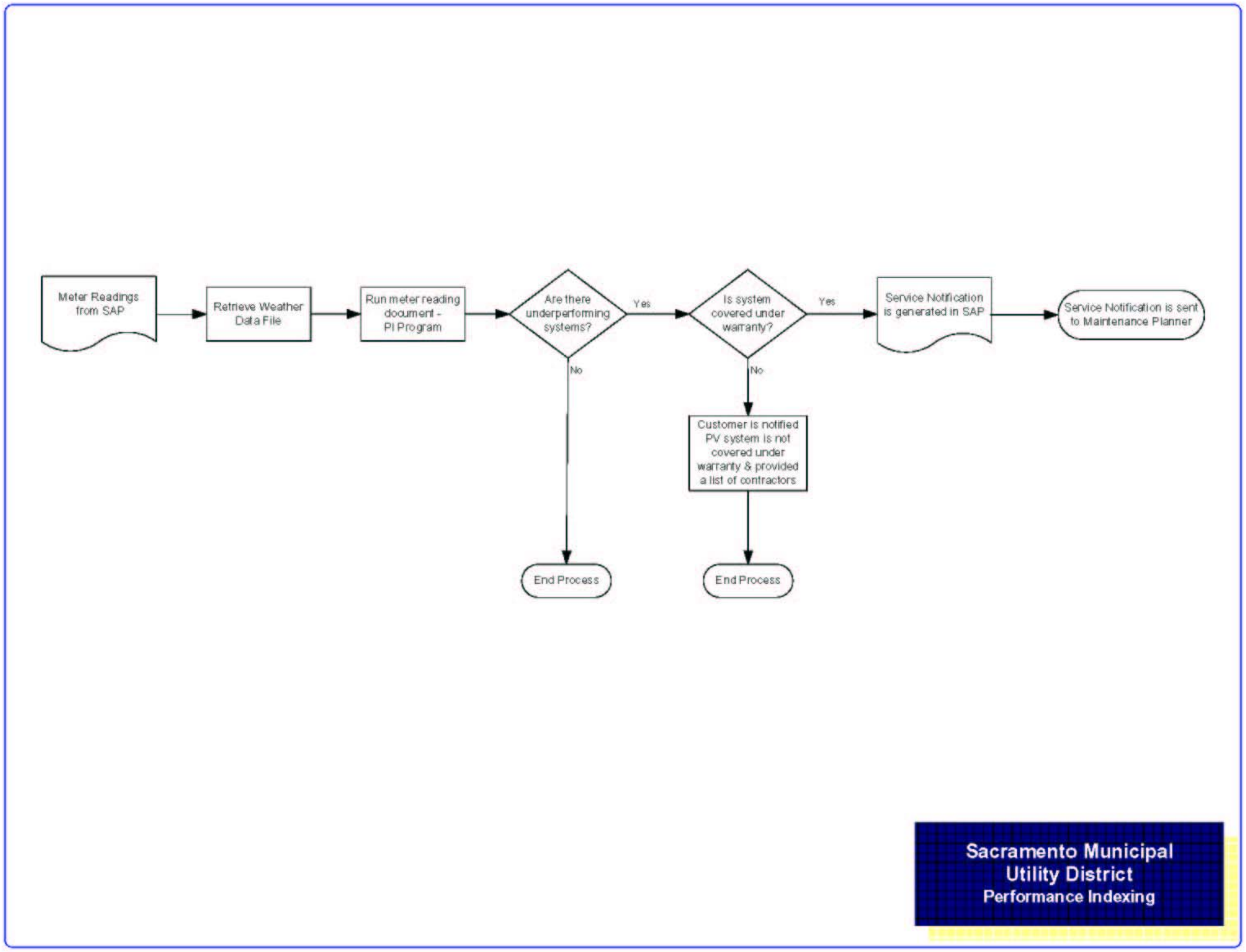
B4. PV Statement Process



B5. PV Maintenance Process



B6. Performance Indexing



B7. SMUD PV System Inspection and Commissioning

SMUD PV SYSTEM INSPECTIONS

1. DOCUMENTATION. Prior to the site visit, the SMUD inspector must have a system description, a wiring schematic of the system, and manuals and technical specifications for the PV modules and the inverter.

2. SAFETY—GROUNDING. Determine if accessible parts of the system have been installed in a code compliant manner, are properly grounded, and are safe for the SMUD inspector (and the homeowner) to touch and evaluate further.

a. Using a DVM, measure dc and ac voltages from the exterior of the dc disconnect, the inverter, the ac disconnect, and the ac service panel (load center) to the grounding electrode (where visible and accessible) or the grounding electrode conductor. If less than 1 volt, proceed. *If more than 10 volts, do not touch any equipment. Call SMUD PV service technicians for an emergency safety shut down of the system.*

b. Open the doors on the dc and ac disconnects and verify that the proper, listed ground-bar kits have been installed. Aluminum lugs bolted to the enclosures with green "tek" screws or sheet metal screws violate the code and may not properly ground the enclosures for the life of the system. If OK, proceed. If not, fill out Service Request.

c. Verify that a green or bare equipment-grounding conductor comes from the PV array through the dc disconnect (connected to the ground bar) to the inverter (connected to a grounding terminal), then through the ac disconnect (connected to the ground bar), and to the ac residential load center (connected to the ground bar). Any metal conduits on dc systems operating over 250 volts should have double nuts (one inside and one outside the enclosure) or use grounding bushings. If OK, proceed. If not, fill out Service Request.

3. SAFETY—OPERATIONAL. Determine if the installed PV system meets the anti-islanding requirements and will shut down when the utility goes off line or out of normal specifications.

a. With the system operating and an ac DVM attached to the ac inverter output, open the ac PV disconnect and verify that the ac voltage on the inverter output goes to zero immediately. This is a basic test and does not verify the full anti-islanding capabilities of the inverter. A better test for PV 2 systems would be to open the main disconnect for the house while monitoring the inverter output. If OK, proceed. If not, fill out Service Request.

4. SAFETY—MAINTENANCE. Determine if the inverter and disconnect switches have been installed in a location that allows space for safe servicing of the equipment when it is energized. This is a code requirement.

a. Verify that there is a clear area around each piece of equipment (dc disconnect, the ac disconnect, and the inverter) that is 30" wide or the width of the component (which ever is wider), that is 36" deep from the front of the equipment, and reaches from the floor or ground to a height of 8 feet. If OK, proceed. If not, fill out Service Request.

b. Verify that the circuit conductors from the PV array have been connected to the line (top) terminals on any dc disconnect. Verify that the circuits from the utility have been connected to the line (top) of the dc disconnects. Grounded conductors should be routed through the disconnects, but not switched. If OK, proceed. If not, fill out Service Request.

5. SAFETY—SITE INSPECTION. The PV system should be installed in a manner that reflects good workmanship that will maximize the long-term safety and durability of the system.

a. All equipment including modules, conduits, cables, disconnects and the inverter should be firmly fastened to the structure. All roof penetrations and wall penetrations should be properly sealed. If OK, proceed. If not, report to the SMUD PV Service Technicians.

b. When exposed single conductor module interconnection cables have been used, these cables shall be firmly and permanently attached to the module frames and mounting racks. Plastic cable ties (even those rated for UV exposure) have not been demonstrated to have sufficient longevity. No conductors shall be loose, touching the roof, or subjected to wind or ice loading. If OK, proceed. If not, fill out Service Request.

6. PERFORMANCE—SITE INSPECTION. The PV system should be installed in a location and manner that maximizes the available solar resource. True south facing surfaces tilted at the local latitude (about 38°) that have no shadows from 9 a.m. to 3 p.m. on December 21 will provide the best mounting orientation. Cooler operation will yield greater outputs and spacing from the roof of 4 inches or greater is preferred.

a. Measure the tilt angle and azimuth orientation from true south of each PV array or subarray. Record these numbers to ensure that the system description is correct in the documentation and is being inserted correctly in the PI program.

b. Using a Solar Path Finder from each of the four corners of the PV array, determine the amount of shading (and reduction in power output from the PV array) for the various months of the year. Evaluate the probability of trees and other plants growing over the years and increasing the amount of shading. If shading is greater than 10% or is expected to be greater than 10% in the next two years, note on report.

7. PERFORMANCE—INVERTER TESTING. Several system performance measurements are made with the system operating. They include inverter performance and array output. The array size, the amount of sunshine, and the amount of shading will determine the power output of the PV array. The inverter should be tracking the peak-power point of the PV array.

a. Using an ac power-quality meter (Fluke 43 B or equivalent) connected to the inverter output with clamp-on current probes, measure the ac power out of the inverter, the current harmonic distortion, and the power factor. Measure the solar irradiance in the plane of the array under clear sky conditions using a pyranometer (such as a Licor SB 200). Using a clamp-on current probe and a DVM, measure the dc input current and voltage to the inverter. *Warning: On systems over 48-volts dc, the PV current measurements should not be made using the internal DVM ammeter functions with the DVM test leads. Arcs to ground, fires, and shocks are possible. A properly-rated, external safety switch should be used with the DVM to make these measurements.*

b. The ac power output from the inverter should be divided by the dc power input (input volts times input amps) to determine the inverter efficiency. The efficiency should be above 90% when the inverter is operating at 50% rated power or higher. The total harmonic distortion (THD) for the ac output current should be no greater than 5% when the inverter is operating at near full power. The power factor should be near unity (0.97 or greater). If OK, proceed. If not, fill out Service Request.

c. Using the measured plane of array irradiance and the nameplate dc rating of the PV array at 25°C (Standard Test Conditions-STC), calculate an expected output for the system under the actual measured irradiance. Measured irradiance divided by 1000 times the predicted full sun output equals the expected output before adjustment for array temperature. The array output will decrease by 0.5% per degree C that the array temperature is above 25°C. Compare the dc power input to the inverter after adjustments for solar intensity and temperature with the STC, nameplate rating. OK if within 10%. If not, fill out Service Request.

*Example: The nameplate rating of the PV system is 2500 watts DC at STC. The measured irradiance in the plane of array near solar neon is 950 watts/m². The array temperature is 45°C. The array power (dc volts times dc amps) at the inverter input is 1300 watts. Adjusting the STC nameplate power for irradiance yields 2000 watts (2500 * 800/1000). Adjusting this value for the 45°C operating temperature give an adjusted output of 1800 watts (2000 (1-0.005[45-25]). The measure output, 1300W, is not within 10% of the expected power of 1800W.*

d. Estimate the PV array voltage peak-power point by measuring module temperature and adjusting the STC rated peak-power point voltage for the array by a calculated adjustment factor based on the temperature and module technology. For silicon, the adjustment is -0.5% per degree centigrade away from 25°C. The inverter dc input voltage should be within 10% of the calculated number. If OK, proceed. If not, fill out Service Request.

Example: The PV array has two strings of module with 12 modules in each string. The peak-power voltage of the module is 34.6V at 25°C from the module data sheet. The array peak-power voltage would be 415.2V (12 x 34.6) at 25°C. The module (array) temperature is measured and is 55°C on the test day and the array voltage is measured at 365 volts. The calculated array peak-power voltage at this temperature is 353V (415.2 x (1- 0.005 [55-25]). The measured and calculated values are within 10%.

8. PERFORMANCE—ARRAY DISCONNECTED. With the array disconnected from the inverter, the open circuit voltage and short-circuit current may be measured and compared with expected values to give an additional evaluation of the condition of the array and the modules. The open-circuit voltage is a strong function of array temperature. The short-circuit current is a strong function of irradiance.

a. Measure the array open circuit voltage at the dc disconnect, or combiner box when multiple strings are used. Adjust the voltage for the array temperature (measured previously). For silicon modules, the adjustment factor is about -0.39% per degree C that the temperature differs from 25°C. OK if within 10% of the standard test condition (STC) value at 25°C. If not, fill out Service Request.

Example: The array has strings of 22 silicon modules in series. Each module has an open-circuit voltage of 21.8 volts at 25°C (STC from the module data sheet). For 22 modules in series, the 25°C open-circuit voltage would be about 480V (22 x 21.8). The measured open-circuit voltage at a module temperature of 60°C is 420 volts. Adjusting the 480 V 25°C string open-circuit voltage to a value at 60°C yields 414 V = (480 x 1-.0039[60-25]). The measured voltage of 414V is within 10% of the calculated voltage of 420.

b. Measure the short-circuit current. *Warning: On systems over 48-volts DC, the PV current measurements should not be made using the internal DVM ammeter functions with the DVM test leads. Arcs to ground, fires, and shocks are possible. Connect the ammeter to an open-circuited, DC-rated, heavy-duty, shorting switch. Connect the ammeter to the switch (or use a clamp-on ammeter), connect the switch/disconnect to the array wiring (each separate string) and then use the switch to close and short the circuit.*

Multiply the short circuit current by the measured plane of array irradiance and divide by 1000. If this value is within 10% of the STC 1000 W/m^2 value, then OK. If not, fill out Service Request.

c. Repeat open circuit voltage and short-circuit current measurements for each string, when the strings can be separated.

9. FURTHER TROUBLESHOOTING

a. Individual strings may be disconnect at rooftop wiring boxes and measured. This will isolate problems to specific strings, not connected at ground level.

b. IV curves can be made using IV curve tracers to pinpoint other problems in the PV array such as module mismatch, failed modules, and shorted bypass diodes.

B8. SMUD PV System Inspection and Commissioning Checklist

ITEM #	DESCRIPTION	OK	NOT OK
1	**Documentation**		
a	System Description?		
b	Schematic Diagram?		
c	Inverter Manual?		
d	Module Manual?		
e	Performance Index Output?		
2	**Safety—Grounding**		
a 1	Inverter enclosure less than 10 volts ac & dc to ground?		
2	DC disconnect enclosure less than 10 volts ac & dc to ground?		
3	AC disconnect enclosure less than 10 volts ac & dc to ground?		
b 1	DC disconnect enclosure properly grounded?		
2	AC disconnect enclosure properly grounded?		
c 1	DC equipment-grounding conductors properly installed?		
2	AC equipment-grounding conductors properly installed?		
3	Metal conduits properly terminated?		
3	**Safety—Operational**		
a	Inverter shutdown?		
4	**Safety—Maintenance**		
a	Installation clearances?		
b	AC and DC Disconnects properly wired?		

c	Grounded conductors properly wired?		
5	**Safety—Site Inspection**		
a 1	Equipment firmly fastened to surface?		
2	Penetrations sealed?		
b	Module wiring attached to frames and racks?		
6	**Performance—Site inspection**		
a	PI output rating =		
b	Shading percentage now = Estimate in 2 years=		
7	**Performance—Inverter Testing (Array Connected-System On)**		
a 1	AC power output = watts		
2	Current THD = %		
3	Power factor =		
4	Module temperature = °C		
4	Irradiance = W/m^2		
5	DC voltage = volts? Within 5% of temp.-corrected value?		
6	DC current = amps?		
7	DC power = watts? Within 10% of PI prediction?		
b 1	Efficiency = Greater than 90%?		
2	THD 5% or less?		
3	PF .97 or higher?		
8	**Performance—Array Disconnected**		
a	Open-circuit voltage = volts. After correction for module temp., within 10% of STC voltage?		
b	Short-circuit current = amps. After correction for irradiance, within 10% of STC current?		
c	String 2 V_{oc} =		
	String 2 I_{sc} =		
	String 3 V_{oc} =		
	String 3 I_{sc} =		
	String 4 V_{oc} =		
	String 4 I_{sc} =		
	String 5 V_{oc} =		
	String 5 I_{sc} =		
	String 6 V_{oc} =		
	String 6 I_{sc} =		

Appendix C

Suggested Draft PV Procurement Technical Specification for SMUD-Owned PV Systems Over 25 kW

5.1 General

5.1.1 The intention of this purchase is to obtain a fully functional Solar Photovoltaic Power System (SPVPS). The SPVPS will be located at the "Jobsite" which is wholly within the SMUD service area.

5.1.2 The Solar Photovoltaic Power System shall be designed to properly operate in an ambient temperature range of XX°F to YYY°F. If any portion of the system requires different temperatures than the range given, the required temperature range and methods used to obtain such an environment shall be SPECIFICALLY NOTED and DESCRIBED in the proposal.

5.1.3 Average Annual Rainfall: ZZZ inches (with afternoon thunderstorms in July and August containing blowing dust and/or rain). Average annual snowfall XXX inches. Average snow depth less than ZZ inches.

5.1.4 Additional Warranties: The Contractor shall provide a two-year, on-site Photovoltaic Power System repair, maintenance and replacement warranty. The Contractor shall also provide a minimum five-year warranty for the inverters. The modules used must have a minimum 20-year warranty.

5.1.5 Photovoltaic Power System Experience: The Contractor shall provide information that the PV power system is current technology and that the Contractor has installed and has in service one or more photovoltaic power systems of configuration being proposed, each with at least 25 kW_{ac} output. A list of systems installed and at least two references must be provided.

5.1.6 The Equipment & Materials shall be designed for safe and easy unattended operation and for safe and easy maintenance, removal, and/or replacement of all components.

5.6 Submittals

5.6.1 The word "submittals" shall be interpreted to include drawings, data, certifications, material safety data sheets, and other items furnished by the Contractor for approval, information, and other purposes. Submittals shall be via US First Class Mail or by overnight delivery service.

5.6.2 The Contractor shall provide design documents detailing the following information:

5.6.2.1 Outline dimensions, services, foundations, and mounting details.

5.6.2.2 Assembly drawings, shop drawings, and all civil/structural drawings.

5.6.2.3 System Description including one line diagrams, electrical schematics, connection and interconnection diagrams, control logic diagrams, conduit and cable schedules.

5.6.2.4 A list of all electrical materials and equipment proposed with specifications and any listed information.

5.6.2.5 Grounding plans.

5.6.2.6 General arrangement plan showing equipment locations.

5.6.2.7 Cable and field wiring installation reports covering field wiring continuity and insulation.

5.6.2.8 Calculations for the ampacity of all conductors and the ratings of switchgear and overcurrent devices.

5.6.2.9 Design summary sheets.

5.6.2.10 Calculations for the voltage ratings of all conductors, switchgear and overcurrent devices.

5.6.2.11 Information showing how non-listed electrical equipment meets the requirements of the NEC.

5.6.2.12 Equipment details and description.

5.6.2.13 Performance of equipment components and subsystems.

5.6.2.14 Controls, monitoring and instrumentation.

5.6.2.15 Performance monitoring.

5.6.2.16 Appendix B—SMUD Interconnection Guidelines.

5.6.3 A QA/QC program shall be submitted covering the PV system (including PV modules, inverter, and other major system components).

5.6.4 A factory test plan shall be developed and submitted covering the inverter. The reports shall be certified.

5.6.5 Certified factory test reports on major equipment such as transformers, switches, and breakers, and field test reports on overall system performance.

5.6.6 An O&M manual as described in Section 5.16.

5.15 Codes and Standards

5.15.1 The material and workmanship furnished by the Contractor shall be the best of its kind and in accordance with the latest issues of the applicable code requirements and standards (including latest published case rulings) in force at the date of this Specification.

All Equipment and Materials, tests, and fabrication shall comply with the latest editions of applicable codes, standards, and regulations of the following:

National Electrical Safety Code (NESC)—ANSI C2-2003

National Electrical Code (NEC)—NFPA 70-2005

Occupational Safety and Health Administration (OSHA) Directives

Applicable regional Building Codes, such as UBC—Uniform Building Code

National Electrical Manufacturers Association (NEMA)

Underwriters' Laboratories, Inc. (UL)

UL 1703, Flat Plate Photovoltaic Modules and Collectors

UL 1741, Static Inverters and Charge Controllers for use in Photovoltaic Power Systems

IEEE 1262, Recommended Practice for Qualifications of Photovoltaic Modules

Certification of PV Equipment: All PV modules, inverters, and electrical components shall be listed by an appropriate and recognized United States Safety Laboratory (for example: UL, ETL, etc.).

ANSI/ASCE 7-99, Building Code Requirements for Minimum Design Loads in Buildings and Other Structures

FCC Regulations Electromagnetic Interference (EMI) Part 15, Subpart A, Subpart B, Subpart J, October 1992

IEEE SCC21 P1547, Recommended Practice for Utility Interconnection

5.15.2 In addition to the above, the Equipment & Materials shall comply with all applicable local, state, and federal codes, standards and regulations having jurisdiction in the area where the equipment or Work shall be installed.

5.15.3 All materials and equipment used in connection with this work shall be new, listed by Underwriters Laboratories Inc., shall meet their requirements, bear their label wherever standards have been established and label service is regularly furnished by that agency.

5.16 Installation, Operation & Maintenance Manuals

Contractor shall provide one complete and bound and one electronic CD copy of an Installation, Operation & Maintenance Manual(s) prior to equipment arrival on-site. Any revisions made by the Contractor shall be IMMEDIATELY provided to the Buyer. The manual shall include:

- A description of the operation of the system and major components.
- A description of all routine maintenance requirements and schedules, and contain instructions on how to perform all required work.
- A section (or a separate manual shall be provided) on the data acquisition system and control system to include full descriptions, schematics, and equipment manuals.
- Warranty provisions and the process (and contacts) to obtain warranty claims work.
- Recommended spare parts.
- All "as-built" installation/construction, operating, and maintenance drawings.

6.1 General Technical Requirements

6.1.1 The Contractor shall provide a turnkey roof-mounted, fixed, flat plate Solar Photovoltaic Power System (SPVPS). The Contractor shall provide turnkey design, engineering, materials, delivery, installation and commissioning of a cost-effective and energy efficient Solar Photovoltaic Power System.

6.1.2 The SPVPS array shall be installed on ______________

6.1.3 The proposed mounting arrangement for the SPVPS array shall minimize the need for roof penetrations.

6.1.4 The design rating of the photovoltaic power system shall be based on the utilization of the available _________ roof area or a minimum of 25 kW AC.

6.1.5 The design output of the PV system shall be 480 VAC, 3-phase, 4-wire wye, 60 Hertz.

6.1.6 The Balance of System (BOS) components shall be installed in a specified fenced enclosed area adjacent to the ____________________.

6.1.7 The SPVPS system will be designed and installed in full compliance with the current Codes and Standards as listed in Section 5.15.

6.2 Work Scope—Items Provided by Contractor

The Contractor shall supply all labor, equipment, and materials necessary to complete the scope of work described in this Specification including:

6.2.1 Design, qualify, fabricate, and assemble, the complete SPVPS that meets the requirements delineated herein including the following:

6.2.1.1 Grid interface equipment, including AC isolation transformer with voltage output as described in section 6.1.4 to match utility secondary distribution voltage.

6.2.1.2 Isolation transformer utility side disconnect switch.

6.2.2 Provide a preliminary Design Package for Buyer's approval. The Design Package shall include Installation and Operations and Maintenance Manuals that provide all aspects of design, installation, operation and maintenance.

6.2.3 Provide Design Drawings and Details of Solar Photovoltaic construction, including building interfaces, system coordination, interconnections, and protocols, as specified below:

1. System and Component Specifications
2. Component and Assembly Drawings
3. Hazards and Operability Analysis
4. Control Logic Description
5. Acceptance Test Plan
6. Site Interface Requirements, including:
   a. AC grid interconnection to which power will be exported, and from which system start-up power will be imported;
   b. DC connections from solar array modules and
   c. Control connections to site

6.2.4 All mechanical & structural calculations, drawings, documents, and reports, demonstrating compliance with this Specification and showing evidence of a minimum (20-year) design life for the entire SPVPS.

6.2.5 Equipment lists of all electrical equipment showing manufacturer, type, and part number. NOTE: Any on- or off-site assembled electrical equipment that is not listed (examined for safety by a nationally recognized testing laboratory such as Underwriters Laboratory (UL)) shall be documented as being fully compliant with the requirements of this Specification and will use only fully listed (not "recognized") components. Specific approval by the purchaser shall be required before any unlisted equipment is used.

6.2.6 Provide a minimum of five person-days start-up technical support including travel to job site and per diem.

6.2.7 Supply spare parts at Purchaser's option (these items to be priced separately from the Lump Sum Price, but are to be guaranteed prices).

6.2.8 Prior to Final Acceptance, Contractor shall conduct a training class for Buyer's Operating & Maintenance personnel. The training class shall last a minimum of 16 hours (split between classroom and "hands-on"), and shall be aimed at familiarizing personnel to trouble shoot, maintain, and operate the entire system properly.

6.2.9 The Contractor shall remain available by telephone, email, or fax and provide consultation to Purchaser on the system (including inverter) malfunctions during the warranty period.

6.2.10 Prior to system acceptance, the Contractor shall be responsible for maintenance of entire system up to point of interconnection interface.

6.2.11 After acceptance by Purchaser, maintenance not covered by warranty and initial troubleshooting will be performed, as required by Purchaser's personnel.

6.2.12 Manuals as described in Section 5.

6.2.13 *Appendix B of SMUD Interconnection Guidelines for Distributed Generators.*

6.2.14 Performance calculations for power system warranty including guaranteed output capacities, and other relevant performance parameters including the basis for the predictions.

6.2.15 Project Schedule

6.2.16 Certified equipment test reports and field test reports (see Section 5.6).

6.2.17 QA/QC Program shall be submitted covering the SPVPS.

Final Drawings corrected to "as-built" conditions.

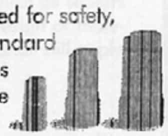
Appendix D

King Safety Wire Connector Series 602

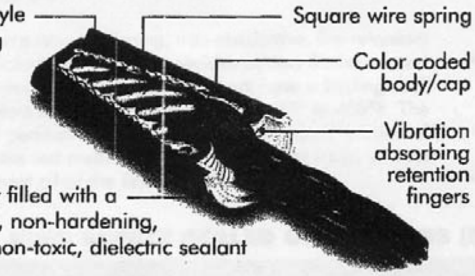
DRY AND DAMP

PRESSURE TYPE/486C TESTED

King's added safety connectors are for use everywhere old style twist-ons have been used. Engineered for safety, King's Dry and Damp Connectors will add extra maintenance-free service life and security to standard electrical systems. Controlling flashover, internal arcing, sparking and fire, each King connector insures a more reliable splice. King's "Safety Action Spring™", lubricated with silicone sealant, draws the conductors deeper insuring maximum continuity and a cooler, energy efficient splice.



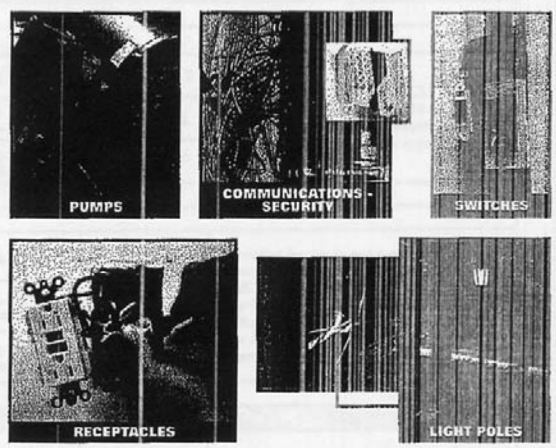
FEATURES/BENEFITS



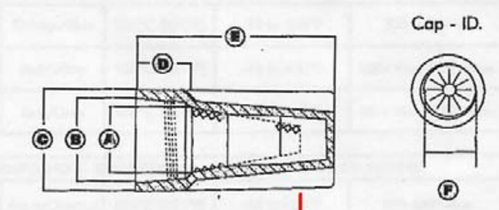
USES/APPLICATIONS

For maintenance-free "added safety", specify everywhere old style twist-ons have been used. Specify in all rated enclosures and everywhere atmospheric conditions or minor condensation are a threat to the splice. (Specification information on back cover.)

- All indoor splices
- All junction boxes
- Motors
- GFCI's
- Small fixtures
- Luminaires
- Security and sound systems
- Swimming pool clock timers
- Interior and exterior light receptacles and switches
- Lighting and control circuits
- Pedestal lighting



MEASUREMENTS



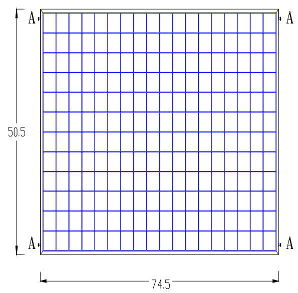
SERIES NO.	#601 Orange/Blue	#602 Red/Yellow	#603 Blue/Gray
A	1/4" (6.35 mm)	7/16" (11.11 mm)	33/64" (13.09 mm)
B	11/32" (8.73 mm)	17/32" (13.49 mm)	43/64" (17.06 mm)
C	7/16" (11.11 mm)	21/32" (16.66 mm)	13/16" (20.63 mm)
D	13/32" (10.31 mm)	27/64" (10.71 mm)	29/64" (11.50 mm)
E	27/32" (21.42 mm)	1-5/16" (49.26 mm)	1-9/16" (39.61 mm)
F	9/32" (6.86 mm)	7/32" (11.43 mm)	7/16" (11.43 mm)
WIRE RANGE	3 #22-1 #12 *	6 #22-1 #8 *	4 #14-2 #6 w/1 #12 *
TEMP.	105°C (221°F)	105°C (221°F)	105°C (221°F)
VOLTS	300-600V MAX.	600V MAX.	600V MAX.

* No pre-twisting necessary.

SMUD: Series 602

CODE/LISTINGS & MARKS

- King Dry & Damp Connectors are listed UL 486C ZMVV and CSA Certified STD. C22.2 #188.
- Meets the NEC Article 370-16 and 352-7 size requirement for equipment in a junction box with sufficient free space.
- Identified for use in the environment of damp locations and other deteriorating agents according to 110-11 of the NEC.



MOUNTING PIN ASSEMBLY, "A"
2 PLACES BOTH ENDS

OR SEALANT-FILLED TWIST-ON ELECTRICAL
S (CU TO CU SPLICES ONLY)

pplicable to sealant filled twist-on wire connectors. The intent of this spec-
echanical, design and performance requirements within which all sealant
d reliably. It is not intended to impose restrictions upon design or mate-
. and NEMA standards not mentioned in this specification shall still apply.

ugh fire retardant color-coded thermoplastic. It shall be made from durable, abrasion resistant, non-hygroscopic materials. It shall include a vibration-absorbing cap with retention fingers and wings for easy grip.

- Inside shall be a non-hardening, non-conductive, fire-retardant dielectric silicone sealant that provides added flashover and corrosion protection. The sealant shall not have a limiting shelf life. The sealant temperature range shall be -45° to 400°F. The sealant shall perform as stated in the "requirements" section of Table B per the test methods listed. The sealant must, without exception, meet all of the listed requirements.

- The connector shall have a plated, conical, square-wire live action spring to draw in conductors deeply and securely in as torque is applied. The live action expandable spring shall provide continuous vibration resistance and holding power through constant temperature changes for solid and stranded wire combinations for #22 to #6.

- All connectors shall be rated for a maximum voltage as indicated in Table A.

- All connectors shall have a temperature rating as indicated in Table A.

- All connectors shall be U.L. Listed and C.S.A Certified.

TABLE A: KING SAFETY SEALED CONNECTORS (FOR CU/CU CONNECTIONS ONLY)

Series No.	Color	Temperature	Silicone Sealant Temperature	Voltage		Solid or Stranded Min / Max	Code/Listing Marks
DRY & DAMP: PRESSURE TYPE / UL / CSA							
601	Orange/Blue	105°C (221°F)	-45 to 400°F	300-600V Max.	Bldg. wiring	3 #22 - 1 #12	Listed UL 486C ZMW and CSA Certified STD. Meets NEC Article 370-16 and 352-7 size requirement for equipment in a junction box with sufficient free space.
602	Red/Yellow	105°C (221°F)	-45 to 400°F	600V Max./1000V Max.	Bldg. wiring In signs & fixtures	6 #22 - 1 #8	
603	Blue/Gray	105°C (221°F)	-45 to 400°F	600V Max./1000V Max.	Bldg. wiring In signs & fixtures	4 #14 - 2 #6 w/1 #12	
WATERPROOF : WATERTIGHT / RAINTIGHT / UL 50 TESTED							
621	Aqua/Orange	105°C (221°F)	-45 to 400°F	300-600V Max.	Bldg. wiring	3 #22 - 1 #12	Identified for use in wet locations and harsh environments according to UL 50 testing and NEC 110-11. Listed UL 486C ZMW and CSA Certified STD. CC22.2 #188. Meets NEC Article 370-16 and 352-7 size requirement for equipment in a junction box with sufficient free space.
622	Aqua/Red	105°C (221°F)	-45 to 400°F	600V Max./1000V Max.	Bldg. wiring In signs & fixtures	6 #22 - 1 #8	
623	Aqua/Blue	105°C (221°F)	-45 to 400°F	600V Max./1000V Max.	Bldg. wiring In signs & fixtures	4 #14 - 2 #6 w/1 #12	
UNDERGROUND: DIRECT BURY / UL / CSA							
106	Lt. Blue	75°C (167°F)	-45 to 400°F	600V Max./1000V Max.	Bldg. wiring In signs & fixtures	3 #22 - 1 #10	Listed for direct burial according to UL 486D test standard. Meets federal specifications W-S-610D and are CSA C22.2 #198.2 Certified. Splices can be used with or without a junction box and/or in metallic or non-metallic wireway as specified by Articles 110-14(b), 300-5(e), 305-4(g), 352-7, 362-7 and 362-21 of the NEC.

TABLE B:

* The percentages for separation and evaporation are by weight lost from the overall sample.

Property	Method	Requirement
Color	Visual	White
Appearance	Visual	Smooth
Oil Separation, 24 hours at 100°C	FTM 791 Method 321.2	1% * Maximum
Evaporation, 24 hours at 100°C	ASTM D972	1% * Maximum
Copper Corrosion, 24 hours at 150°C	ASTM D4048	No Corrosion

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Web: www.kingsafety.com • E-mail: kingsafety@stlnet.com • • US Patent #B 5,113,037